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Human Systems Integration Synthesis Model for Ship Design

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THESIS

HUMAN SYSTEMS INTEGRATION SYNTHESIS MODEL FOR SHIP DESIGN

by

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September 2012

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13. ABSTRACT (maximum 200 words)

Current fiscal constraints are driving the reduction of system life cycle cost (LCC). A key objective of HSI is the reduction of operational cost and the improvement of operational performance. This thesis seeks to develop a Human Systems Integration (HSI) Synthesis Model for Ship Design. This model is based on the premise that ship design characteristics interact with the domains of HSI. The thesis begins with an historical overview of ship architecture and technology and their interactions with the domains of HSI. The HSI Synthesis Model for Ship Design was developed using the Framework of Naval Postgraduate School's Systems Engineering Ship Synthesis Model. Quantitative data analysis was conducted using Offshore Patrol Vessel (OPV) design data from Information Handling Services (IHS) Jane's database. The data analyzed included 35 ships from 21 nations. Multiple regression analysis consisted of nine independent ship design variables and a response variable of manpower. Data analysis revealed that ship length and ship draught were statistically significant. The proposed HSI Synthesis Model accounted for 49% of the variance of crew complement. This thesis lays the foundation for future qualitative and quantitative analysis of the interaction between ship design characteristics and HSI domains. Additionally, it provides an initial HSI model that can be expanded upon by including additional HSI domains and, ultimately, may lead to a viable design tool for HSI practitioners and systems engineers.

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HUMAN SYSTEMS INTEGRATION SYNTHESIS MODEL FOR SHIP DESIGN

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ABSTRACT

Current fiscal constraints are driving the reduction of system life cycle cost (LCC). A key objective of Human Systems Integration (HSI) is the reduction of operational cost and the improvement of operational performance. This thesis seeks to develop a HSI Synthesis Model for Ship Design. This model is based on the premise that ship design characteristics interact with the domains of HSI. The thesis begins with an historical overview of ship architecture and technology and their interactions with the domains of HSI. The HSI Synthesis Model for Ship Design was developed using the Framework of Naval Postgraduate School's Systems Engineering Ship Synthesis Model. Quantitative data analysis was conducted using Offshore Patrol Vessel (OPV) design data from Information Handling Services (IHS) Jane's database. The data analyzed included 35 ships from 21 nations. Multiple regression analysis consisted of nine independent ship design variables and a response variable of manpower. Data analysis revealed that ship length and ship draught were statistically significant. The proposed HSI Synthesis Model accounted for 49% of the variance of crew complement. This thesis lays the foundation for future qualitative and quantitative analysis of the interaction between ship design characteristics and HSI domains. Additionally, it provides an initial HSI model that can be expanded upon by including additional HSI domains and, ultimately, may lead to a viable design tool for HSI practitioners and systems engineers.

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LIST OF ACRONYMS AND ABBREVIATIONS

ACT	American College Test
ASVAB	Armed Service Vocational Aptitude Battery
CBA	Capability Based Assessment
CG	Missile Guided Frigate
CM	Corrective Maintenance
DAG	Defense Acquisition Guide
DAU	Defense Acquisition University
DDG	Missile Guided Destroyer
DoD	Department of Defense
DOE	Design of Experiments
DTE	Detect to Engage
EEZ	Economic Exclusionary Zone
FFG	Missile Guided Frigate
FM	Facilities Maintenance
GAO	General Accounting Office
HFE	Human Factors Engineering
HSI	Human Systems Integration
HSIP	Human Systems Integration Plan
KSA	Knowledge, Skills, and Abilities
LCS	Littoral Combat Ship
LHA	Amphibious Assault Ship
LPD	Landing Platform Dock Ship
MATB	Multi-Attribute Test Battery
MDA	Maritime Domain Awareness
MIO	Maritime Interdiction Operations
MOE	Measures of Effectiveness
MOP	Measures of Performance
MRPA	Make Ready Put Away Allowance
NICOP	Naval International Cooperative Opportunities in Science & Technology Program
NPS	Naval Postgraduate School
NPRST	Navy Personnel Research, Studies, and Technology

OM	Operational Manning
OMOE	Operational Measure of Effectiveness
ONR	Office of Naval Research
OPV	Off-Shore Patrol Vessel
OSM	Operational Simulation Model
OUS	Own Unit Support
PA	Productivity Allowance
PC	Principal Component
PCA	Principal Component Analysis
PM	Preventive Maintenance
SAT	Scholastic Aptitude Test
SD&T	Service Diversion and Training
SSM	Ship Synthesis Model

EXECUTIVE SUMMARY

This thesis provides a qualitative and quantitative evaluation of how ship design characteristics interact with the domains of Human Systems Integration (HSI). The qualitative analysis consisted of an in-depth discussion of ship design theory and ship design characteristics. The qualitative analysis also consisted of an historical perspective that evaluated how ship design technological advances throughout history impacted the domains of HSI. The quantitative analysis consisted of both Principal Component Analysis and Multiple Regression. Principal component analysis was necessary to determine which ship design characteristics or variables were more likely to account for the variance in crew complement (manpower). The second quantitative analysis used during this study was multiple regression. Multiple regression was used to fit a model capable of predicting crew complement (manpower) for Off-Shore Patrol Vessels (OPVs). In addition to qualitative and quantitative analysis, this thesis proposed a Humans Systems Integration Synthesis Model for Ship Design. This model describes how HSI domains interact with input variables determined by both capability requirements and physical constraints (ship design characteristics). This model lays the groundwork for future quantitative analysis capable of modeling and predicting response variables contained in HSI domains. This thesis concluded that ship design characteristics interact with the domains of HSI and can be evaluated with both qualitative and quantitative analysis. Additionally, this thesis concluded that relationships between ship characteristics and HSI domains can be specified and modeled using both Principal Component Analysis and Multiple Regression analysis. Recommendations for future research include further qualitative and quantitative analysis of additional HSI domain attributes; historical perspectives and quantitative analysis of additional systems besides ships; continued refinement of the HSI Synthesis Model for Ship Design; integration of this thesis manpower model with the Navy’s current manpower model. The limitations of this study were the small sample size selected for multiple regression,

based on the number of independent variables. Additionally, the study only considered OPVs and did not account for cognitive and task functions that may impact manpower predictions.

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I thank my thesis adviser, Dr. Lawrence Shattuck, and second reader, Dr. Eugene Paulo, for their guidance and professionalism during this process. Specifically, I thank Dr. Paulo for both planting the seed that led to this thesis and giving me the opportunity to participate in the Naval International Cooperative Opportunities in Science & Technology Program (NICOP) initiative. Additionally, I would like to emphasize Dr. Shattuck's dedication and leadership by ensuring my work lived up to the highest of expectations.

Most importantly, I thank my wife, Deanna, and our two children. Your unconditional love, support and patience have given me the support I needed to succeed during this challenging process. My success here at Naval Postgraduate School would not have been possible without my wife's support, and I am forever grateful.

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I. INTRODUCTION

A. PROBLEM STATEMENT

Historically, the naval engineering process has focused on weapon systems activities, vice the utilization of a human centered design approach. In general, capability gaps have had little to do with human performance and more to do with system performance. The Office of Naval Research (ONR) has acknowledged this as a problem worthy of further research and evaluation. ONR intends to acquire systems capable of maximizing the output of the Navy's Human Capital. The term Human Capital is defined by Kaplan and Norton (2004, p. 13) as, "employees' skills, talent, and knowledge." ONR's objective of developing systems as a means to enhance human performance is supported by the following:

> The Navy and Marine Corps are seeking the development of innovative technology-based products to enable transformation in their Human Capital programs, targeted at Human Systems Integration (HSI), that enable Naval Enterprise program managers to optimize total system performance, minimize total ownership costs, and ensure that systems are built to accommodate the characteristics of the user population that will operate, maintain, and support systems, for the warfighting pillars of Sea Strike, Sea Shield, Sea Basing, and FORCEnet. (Krebs, 2008, p. 1)

This thesis research effort was conducted in conjunction with the Naval International Cooperative Opportunities in Science & Technology Program (NICOP) initiative. This joint venture investigated whether a model that incorporates ship characteristics and inputs from the domains of HSI will lead to ships with better total system performance. The combined efforts of the NICOP initiative and this thesis will contribute to the development of a computer-based model capable of addressing cost and overall system performance, including HSI considerations, of an Off-Shore Patrol Vessel (OPV) currently being designed by the Italian Navy.

The OPV is a cost effective solution for nations desiring to improve maritime security along their coastline, contribute to freedom of navigation, and patrol their

economic exclusionary zone[1] (EEZ). In general, OPVs displace less than 2,000 tons, are between 150 and 300 feet in length, possess crew-served armament and short-range missiles, and employ relatively small crews. The mission areas supported by OPVs consist of Anti-Surface Warfare and Maritime Interdiction Operations. Anti-Surface Warfare is the ability to engage other surface ships at sea. Maritime Interdiction Operations (MIO) enforce coastal law. Typical MIO missions include intercepting contraband or persons of interest at sea. Since this class of warship is relatively small and lacks the complexity of larger vessels, it was ideal for establishing a baseline design model.

Outside of extensive task analysis or trial and error, how does a nation determine HSI requirements for its ships? This thesis addressed this issue from an historical perspective and focused on the HSI domain of manpower. An analysis of previous ship designs revealed information about the links between ship design and the domains of HSI, in particular, the domain of manpower. In addition to an historical perspective, a quantitative analysis was conducted in an attempt to identify a method to forecast manpower requirements based on ship design characteristics. This process will aid future HSI practitioners and systems engineers in conducting HSI domain tradeoff analyses.

B. OBJECTIVES

This research intends to define and explain relationships between ship characteristics and domains of HSI. The primary objectives of this study are as follows.

- Assess how ship characteristics impact the domains of HSI
- Assess HSI domain trade space, given a set of ship characteristics
- Develop and assess a model capable of explaining the relationships between HSI domains and ship characteristics

[1] The EEZ consist of the waters extending from a nation's coastal waters, 12 nautical miles, out to 200 nautical miles where that nation has the right all resources extracted from the sea (http://www.un.org).

C. RESEARCH QUESTIONS

- How do the domains of Human System Integration interact with the physical characteristics or design specifications of warships?
- How could the specified relationships between ship design and the domains of Humans Systems Integration be incorporated into the design of the OPV?
- Can a model based on the domains of HSI and ship characteristics predict or forecast HSI domain requirements?

D. HUMAN SYSTEMS INTEGRATION

The human is an integral part of any Department of Defense (DoD) weapon system. The idea that humans are central to the design of a system is at the core of HSI. The Naval Postgraduate School (2010) definition of HSI states:

> HSI acknowledges that the human is a critical component in any complex system. It is an interdisciplinary approach that makes explicit the underlying tradeoffs across the HSI domains, facilitating optimization of total system performance in both materiel and non-materiel (DOTLPF) solutions to address the capability needs of organizations.

An interdisciplinary approach to system design is essential to the identification of the overall system trade space. If the HSI process is implemented and successful, total system performance will be optimal and overall lifecycle cost will be reduced. HSI consists of the following domains:

- Manpower
- Personnel
- Training
- Human Survivability
- Occupational Health and Safety
- Habitability
- Human Factors Engineering

HSI is most effective when the appropriate measures of performance (MOP) and measures of effectiveness (MOE) are considered. The tradeoffs made among the domains of HSI enable the DoD to effectively balance time, cost, and performance in the

acquisition process. In order to accomplish the necessary level of human performance, the Navy has developed four strategic HSI objectives according to the FY11 HSI Plan.

- INTEGRATE: HSI into Integrated Acquisition, Technology, Logistics Life Cycle Management Framework to equip and sustain the warfighter
- INSTITUTIONALIZE: HSI as the way of doing business to increase total systems performance and decrease total ownership cost
- SUSTAIN: HSI through collaboration with partners in OSD, sister services, industry, and academia
- IMPROVE: HSI processes through metrics, feedback, and lessons learned (OUSD AT&L, 2010, p. 5).

This thesis aligned with the overall intent of the 2011 HSIP by focusing on integrating the domains of HSI with the system engineering process. The interactions and tradeoff considerations between physical ship characteristics and the domains of HSI were analyzed within the context of a total systems mindset. Collaboration with the Office of Naval Research (ONR) and the Naval Postgraduate School (NPS) Systems Engineering (SE) Department was critical to the development of a model that explains the how operational requirements and system physical constraints impact the domains of HSI. Four of the eight domains of HSI are described below. While the model developed in this thesis focused on the domain of manpower, human factors engineering, personnel, and training also significantly impact HSI and ship design.

Manpower: The Defense Acquisition Guide (DAG) states that, “Manpower factors are those job tasks, operation/maintenance rates, associated workload, and operational conditions (e.g., risk of hostile fire) that are used to determine the number and mix of military and DoD civilian manpower and contract support necessary to operate, maintain, support, and provide training for the system” (DAU, 2012). These factors imply that manpower requirements vary ship to ship based on the type of platform and its mission sets.

In the past, the U.S. Navy has been able to build multi-mission capable warships. Given our highly constrained economic environment and the cost of manpower, the Navy has been forced to consider smaller platforms with customized mission sets. The Littoral Combat Ship (LCS) is considered the prototype for reducing manpower onboard ships

while providing a capability on par with legacy ships currently in our arsenal. This thesis focused on our ability to forecast manpower requirements based on ship design characteristics such as the size of the platform, number of sensors, and number of platform mission sets, level of system autonomy, and training duration of a ship’s crew.

Human Factors Engineering (HFE): The Defense Acquisition University (DAU) definition of the human factor engineering domain states, “HFE is the discipline of applying what is known about human capabilities and limitations to the design of products, processes, systems, and work environments. It can be applied to the design of all systems having a human interface, including hardware and software” (DAU, 2012).

The domain of HFE “discovers and applies information about human behavior, abilities, limitations, and other characteristics to the design of tools, machines, systems, tasks, jobs, and environments for productive, safe, comfortable, and effective human use” (Sander & McCormick, 1993). As ships have grown in size and complexity, technological systems have been added to help Sailors control them. This technology has changed the nature of the work performed by Sailors from manual to cognitive and from direct to supervisory. The technology requires HFE practitioners to design interfaces that provide insight into opaque nature of complex systems. The more technology onboard a ship, the greater the need there will be for HFE. This thesis briefly examined the tradeoffs between ship design characteristics and HFE and their overall impact on operational effectiveness.

Personnel: The DAU definition of the personnel domain states, “Personnel factors are those human aptitudes (i.e., cognitive, physical, and sensory capabilities), knowledge, skills, abilities, and experience levels that are needed to properly perform job tasks” (DAU, 2012). Personnel attributes are those innate abilities that people possess which potentially make them a good fit for a specific career in an organization.

If the DAU definition of personnel is indeed accurate, then a Sailor’s knowledge, skills, and abilities (KSAs) will determine his or her ability to be effective on the job (Hedge et al., 2006). If sailors have the necessary KSAs, they are more likely to achieve

the level of effectiveness required. This thesis also examined the personnel factors that influence the characteristics required for the crew.

Training: The DAU definition of the training domain states, “Training is the learning process by which personnel individually or collectively acquire or enhance pre-determined job-relevant knowledge, skills, and abilities by developing their cognitive, physical, sensory, and team dynamic abilities” (DAU, 2012). Essentially, training consists of gathering knowledge and the development of skills through sensory perception. The job relevant training that one acquires is based on the task to be conducted and the system they intend to operate within. Therefore, the domain of training is influenced by the selected ship design characteristics.

For any platform, the level of training required is a function of the complexity of that platform, and the size of the crew. A more complex system with a smaller crew might demand that each crewmember be skilled in a multitude of disciplines, which may demand longer training periods. Additionally, we need to consider the impact on readiness when manpower decisions require crewmembers to be hybrid sailors. Hybrid sailors are those individuals who are able to perform multiple jobs on the ship but also require an extensive amount of training and may contribute to a loss of readiness if they are somehow lost to the command.

E. THESIS ORGANIZATION

This thesis consists of six chapters. Chapter I is comprised of the problem statement and introduction to the HSI. Chapter II is a literature review of relevant ship characteristics selected for this study and applicable domains of HSI. Additionally, this chapter provides an historical perspective of ship design and its impacts on HSI domains. Chapter III consists of the methodology utilized to identify HSI domain qualitative variables in relation to ship design characteristics selected for this research. Chapter IV includes both qualitative and quantitative data analyses explaining those relationships from Chapter III. Chapter V discusses the results and their implications. Chapter VI provides conclusions and recommendations for extending the work described in this thesis.

II. LITERATURE REVIEW

A. OVERVIEW

This literature review is partitioned into three sections. The first section consists of an overview of ship architectural design and selected ship synthesis variables. The second section consists of an overview of the domains of HSI. The third section consists of an historical analysis of ship design and the significance of technological advances.

B. INTRODUCTION

The physical design of ships and its relationship to human operators is the primary focus of this literature review. In order to understand the impact of ship design on the domains of HSI, one must understand the basic theory and requirements that drive a ship's specifications. The study of physical characteristics is analyzed within an historical framework from the age of sail to the present day. Additionally, this historical perspective will be linked to the domains of HSI. The purpose of this literature review is to illustrate how the ship design characteristics and domains of HSI are interdependent.

Prior to considering ship design characteristics, one must understand the term "functional requirements." DAU's System Engineering Fundamentals guide provides an adequate explanation for defining functional requirements. The guide states, "Functional requirements define quantity (how many), quality (how good), coverage (how far), time lines (when and how long), and availability (how often)" (DAU, 2001). One of the key operational requirements of warships is how fast it can transit in any given scenario. Self-imposed constraints of a ship's physical attributes, such as length or beam, may increase or decrease how fast a vessel can transit. Therefore, functional requirements impact HSI domain tradeoff analysis. The next section of the literature review will discuss the notional NPS Systems Engineering Ship Synthesis Model. The model illustrates how capability requirements manifest themselves in the physical characteristics of the ship, while explaining tradeoffs related to operational and physical (system) constraints.

C. NPS SYSTEMS ENGINEERING SHIP SYNTHESIS MODEL

Figure 1 illustrates a Ship Synthesis Model (SSM) developed by Paulo and MacCalman (2011). This model's development was driven by the need to determine a ship's potential performance given a set of measures of effectiveness and design parameters.

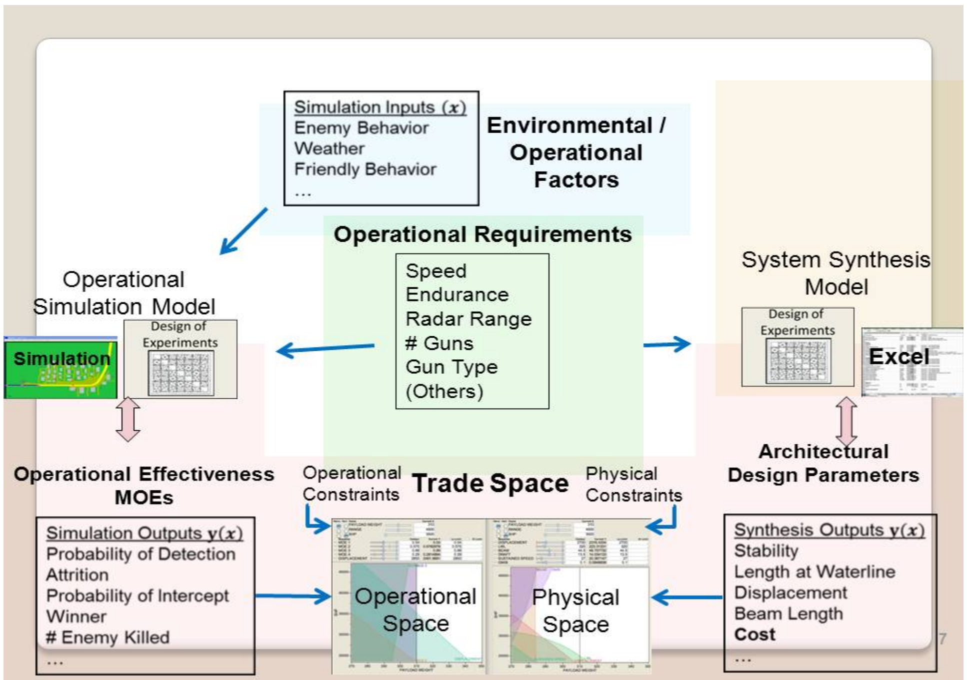

Figure 1. NPS Systems Engineering Ship Synthesis Model (From Paulo & MacCalman, 2011)

The model is based on a ship's operational requirements. Operational requirements are defined by answering the following questions:

> What are the anticipated types and quantities of equipment, software, personnel, facilities, etc., required, and where are they to be located? How is the system to be utilized, and for how long? What is the anticipated environment at each operational site (user location)? How is the system to be supported, by whom, and for how long? (Blanchard & Fabrycky, 2006, p. 59)

The operational requirements shown in Figure 1 are typical examples of ship specific requirements. A close inspection of the NPS Systems Engineering Ship Synthesis Model reveals that it does not contain HSI domain-related requirements, as alluded to and defined by Blanchard and Fabrycky (2006). Stated differently, the NPS Systems Engineering Ship Synthesis Model is currently not integrated with the domains of HSI. This thesis attempts to lay the groundwork and methodology to integrate the domains of HSI into the NPS Systems Engineering model.

The left-hand side of the model illustrates the relationship between the Operational Simulation Models (OSMs) and the Operational Measures of Effectiveness (OMOE). The OSMs are tools that help determine how different operational requirements impact the OMOE. An OMOE is deemed to be the most critical function to a customer or key stakeholder (Blanchard & Fabrycky, 2006). Additionally, simulations that evaluate a specified set of ship characteristics can evaluate platforms operational effectiveness via the design of experiments (DOE). The design of experiments addresses the researcher’s stated hypotheses, while considering the following three principles:

> 1) one cannot prove hypotheses, one can only disprove hypotheses, 2) Thus the recommended strategy for scientific investigation is to design experiments with a view to disproving a hypothesis at hand. 3) If one can formulate a complete set of alternative hypotheses about an issue, then one can design experiments to systematically disprove one after another of the hypotheses until only on non-falsifiable hypothesis remains. (Jacquez, 1998, p. 260)

The right-hand side of the model illustrates the relationship between System Synthesis Model (SSM) and Architectural Design Parameters. The most likely tools to aid in the development of DOE and modeling for the SSM are Excel or JMP. JMP is a statistics software package used in experimental design, Six Sigma, and other analytic processes (JMP, n.d.). Both tools can be used to verify and validate relationships between operational requirements and the ship’s design parameters.

The bottom center portion of the model consists of the trade space, which is divided into operational and physical constraints. The operational constraints place limits on the task or functions for a given scenario. The physical constraints place limitations on

the actual design parameters of the ship. The trade space analyses between operational and physical constraints ensure the optimal ship design will be delivered to the stakeholder based on the operational environment and operational requirements.

For the purpose of illustrating how the trade space process of the synthesis model works, consider making tradeoffs for a ship's speed requirement. If we desire to build a patrol craft that goes 40 knots, we must minimize weight. However, if the ship will operate in a hostile environment, additional armor will increase survivability but add weight. Weight is a physical constraint associated with design parameters that will impact both speed and survivability (after an enemy attack). Operational requirements or physical constraints can be increased or decreased based on sound understanding of the trade space. The next section of the literature review will address ship design characteristics and ship design theory. This section of the literature review will lay the groundwork for the establishing the traceability of HSI domains to ship characteristics.

D. SHIP SPEED

The speed of a ship is driven by the functionality required of the vessel. This writer is not suggesting that physical constraints of engineering do not determine a vessels speed, but it is suggested that functionality drives speed requirements. For example, patrol craft and racing boats functionality dictates that they go fast. Closely related to speed are the physical size constraints of the vessel and its propulsion needs. Since speed is a function of distance and time, those two variables determine the type of propulsion utilized. Propulsion can be provided from numerous sources.

- Manpower—humans rowing the vessel utilizing oars/paddles
- Environment—wind
- Machine—engines: steam, diesel, gas turbine, or nuclear

Prior to establishing a ship's speed requirements, one must understand the forces that impact a ship's ability to transit at sea. Basic ship theory states, "The power required to drive a ship through the water depends upon the resistance offered by the water and

air, the efficiency of the propulsion device adopted and the interactions among them" (Tupper & Rawson, 2001, p. 365). As is evident from this quotation, speed is a multi-faceted ship characteristic.

Prior to the invention of machine-generated propulsion, sailors depended on the wind and ship's sails. Ferreiro (2007, p. 177) states the following as factors affecting ship's speed prior to the advent of mechanical propulsion:

> The speed of a sailing warship of the eighteenth century was dependent on a number of factors, of which hull shape, affecting primarily wave making resistance, was probably one of the least important. By far the most important was the skill of the commander and his crew in choosing the right headings, the speed of maneuvers and furling and unfurling sails, and of course ensuring the upkeep of the ship.

The hull form or shape of the ship was but one factor that determined a ship's speed. The skill of the commander, the training of the crew, and the maintenance of the ship also were key its ability to sail fast. The ship's net speed is, therefore, the result of tradeoffs among physical design considerations such as hull form, displacement, and propulsion, as well as human considerations such as the skill and training of the commander and crew.

E. SHIP DISPLACEMENT

A ship's displacement is a function of its mass and weight. A simplistic description of displacement is Archimedes' Law. The law states, "that when a solid is immersed in a liquid, it experiences an upthrust equal to the weight of the fluid displaced" (Tupper & Rawson, 2001, p. 53). This ship characteristic is once again tied to the required functionality of the vessel. The historical perspective (later in this chapter) will address how changes in building material contribute to the overall mass and weight of a vessel. Another weight consideration is the type and quantity of stores requiring transport. A ship's displacement is also a function of the ship design's length, beam and draught. Therefore, the manipulation of any of these ship characteristic variables has implications for the other variables and overall ship functionality.

F. SHIP LENGTH

The design length of a vessel has both positive and negative consequences. Besides the interactions between the ships beam and draught, the following are tradeoff considerations for increasing a ship's length.

- Generally increases longitudinal sea keeping
- Requires less power
- Difficult to achieve high degree of maneuverability
- Less fuel cost

Additionally, the optimization of this ship characteristic is supported by basic ship design theory. It states that an increase in the length of a ship increases displacement, but reduces power, cost, and reduces fuel consumption (Watson, 1998).

A ship's length will impact its functionality and operational performance. This design variable will interact with human performance, manpower requirements, and overall life cycle cost. For example, poor sea keeping can contribute to seasickness. In general, longer ships provide a more stable platform and, therefore, reduce the likelihood of seasickness. In addition, smaller power requirements could result in a design with fewer engines and maintenance requirements.

Watson (1998, p. 74) noted the following concerning cost and power requirements:

> A first principles approach to the determination of the optimum block coefficient for a ship would involve a trade-off calculation in which the increment in building cost resulting from the increased dimensions required for a fine block coefficient is compared with the saving in operational cost obtained as a result of the reduction in power which fining the lines achieves.

The block coefficient is the standard for evaluating cost versus propulsion requirement scenarios. The block coefficient is expressed with the following formula:

$$C_b = \frac{V}{LBT}$$

Figure 2. Block Coefficient (From Tupper & Rawson, 2001, p. 12)

The notation is defined as follows.

- C_b = block coefficient
- V = volume of water displaced (in tons)
- L = length at waterline (in feet)
- B = beam at waterline (in feet)
- T = draught (in feet)
-

The Froude number in Figure 3 represents the ship's hydrodynamic characteristics. Essentially, hydrodynamics is the study of interactions between water-borne vessels and their interactions with the environment exposed. Additionally, the impacts of hydrodynamics differ depending on the salinity of the body of water. The calculations of the Froude number in this thesis utilize calculations that account for ships operating bodies of water consistent with the open ocean.

The Froude number is expressed with the following formula:

$$Fr = \frac{V}{\sqrt{gL}}$$

Figure 3. Froude number (From Tupper & Rawson, 2001, p. 695)

The notation is defined as follows:

- F_r = Froude number
- V = Ship Velocity (meters per second)
- g = gravity (9.81 meters per second^2)
- L= Ship length at the waterline (in feet)

Since the Froude number contains both a ship characteristic of length and an operational requirement, speed, one could expect it to have direct relationship the HSI domain of manpower. The data analysis of the OPV sample for this thesis reveals a high level of correlation to the crew complement. Additionally, the propulsion requirements may impact the overall crew complement and possibly impact the training and personnel domains.

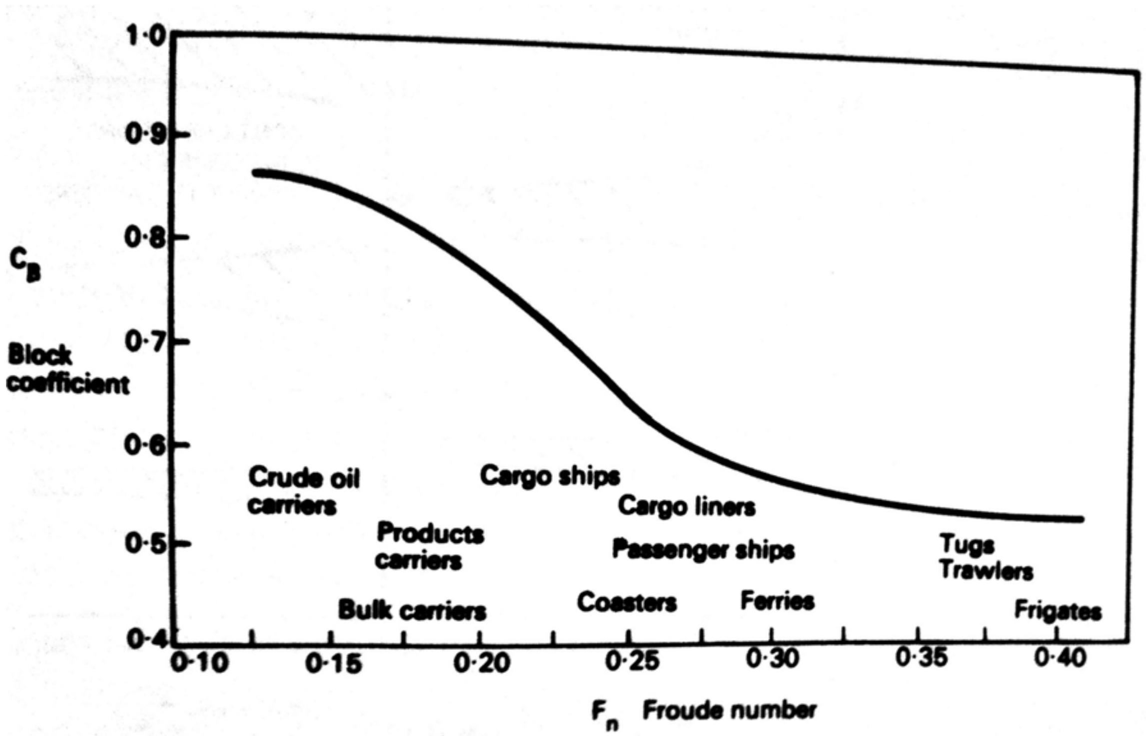

Fig. 15.8 Optimum block coefficient

Figure 4. Optimal Block Coefficient Curve (From Tupper & Rawson, 2001, p. 633)

The optimum block coefficient is an indicator of ship sea-keeping[2] and capacity to support systems that will require a larger shipping volume. Figure 4 provides an illustration of the optimal block coefficients for the most common ship platforms. This figure also shows how the interaction between the block coefficient and Froude number point toward an optimal design of a ship with a specific prescribed functionality

In addition to the block coefficient, ship length is also a factor used to determine the vessel's overall stress as a result of cargo loading and wave impact. The bending moment amidship is the total maximum bending moment that a ship can withstand. As the length of a ship increases its ability to resist load stresses increases (Zubaly, 1996). Therefore, by increasing the length of a ship you increase its capacity to carry loads and increase survivability at sea when encountering powerful wave activity.

[2] Sea-keeping: "During the early design stages of any vessel, an important aspect that should be taken into account is its sea-keeping characteristics (i.e., the way the vessel behaves under various environmental conditions)" (Grech, Horberry, & Koester, 2008).

G. BEAM

A ship’s stability, propulsion, and fuel tankage requirements are impacted by ship beam. The term beam is also synonymous with the term breadth. The basis for the evaluation of vessel requirements is related to the length-beam relationship. The length to beam ratio is an indicator of a vessel’s volume and potential power requirements for propulsion. Figure 5 is a 1975 regression analysis of the beam to length relationships.

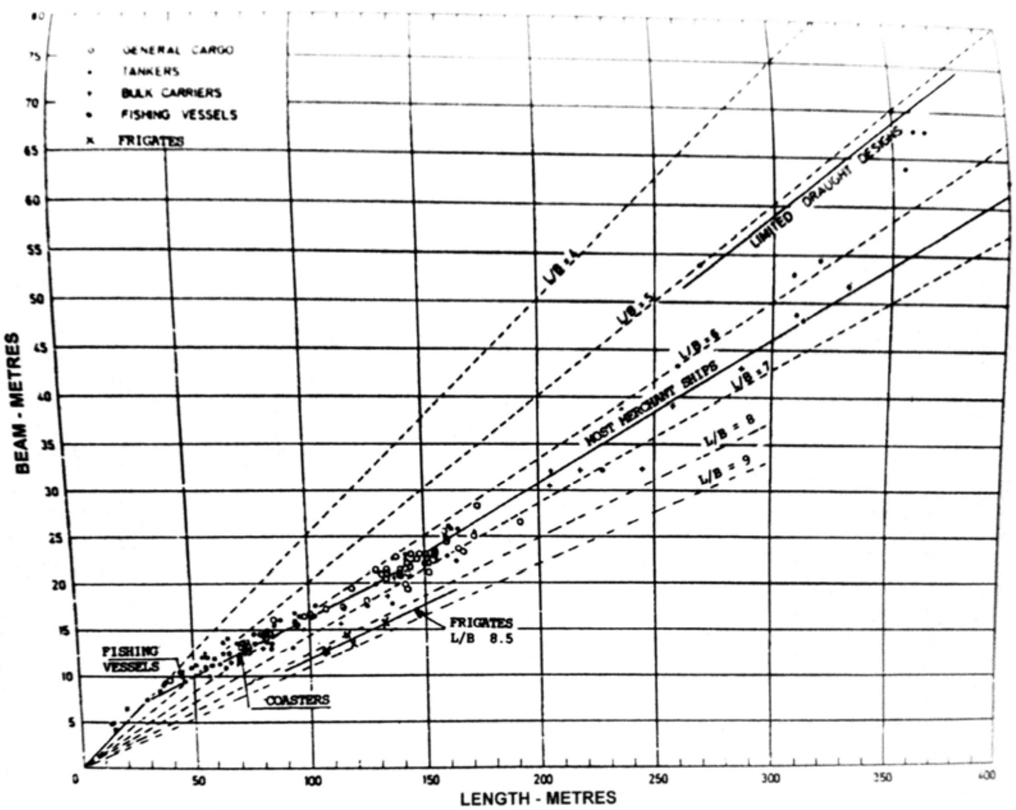

Figure 5. Length-Breadth Relationship (From Watson, 1998, p. 67).

This figure illustrates the linear relationship between the length and beam of a ship, its ratio, and potential to have a large volume capacity. Additionally, notice that fishing vessels are on the lower end of the graph while merchants’ ships are on the higher end.

H. NUMBER OF SYSTEMS BASED ON OPERATIONAL MISSION

Naval warship designs are driven by operational requirements. The policies for the acquisition of new technological systems are described in DoD Instruction 5000.02, Operation of the Defense Acquisition System. A capabilities-based assessment (CBA) identifies the capability gaps that currently exist and then recommend ways to close those gaps in a manner consistent with the nation's overall military strategy. High priority capability gaps lead to requirements that drive ship performance parameters.

Ship characteristics emerge from the design, development, engineering and manufacturing processes. The quantity and type of system are dependent on the mission area where the capabilities will be applied. For example, the system that results must provide the capabilities for which the ship was designed. Additionally, the capability gap will, in most cases, be directly related to a specific mission area. The three major warfare areas are the following.

- Anti-Air Warfare
- Anti-Surface Warfare
- Anti-Submarine Warfare

Figure 6 is an illustration of the basic ship synthesis model. This model describes the manner in which the mission area and measures of performance are determined. The measures of performance determine the measure of effectiveness for the selected system. For example, if the mission is anti-surface warfare, then detection of surface contacts is a measure of performance. The detection of surface contacts is generally conducted via radar; therefore, the measure of effectiveness of the radar is the probability of detection.

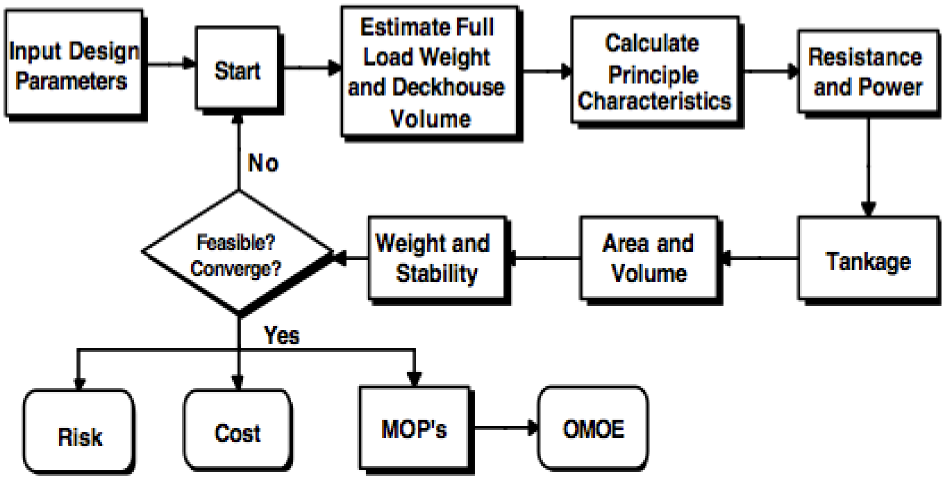

Figure 6. Ship Synthesis Model (From Brown & Salcedo, 2003)

The ship synthesis model Figure 6 illustrates the interaction between the ship characteristic variables and operational measure of effectiveness (OMOE). The input design parameters represent the ideal ship design. The synthesis process takes propulsion, displacement, length, beam, and stability into account to determine if the design is feasible. Essentially, the ship synthesis model assists with the final determination of the number of systems based on the specified mission areas and input design characteristics.

The ship synthesis model is very useful in determining the number of ship systems based on the selected mission area, but the flow of the model is not completely accurate. The ship synthesis model begins with the input of weapon system parameters before defining the warfare area measures of performance. A more effective flow of the ship synthesis should begin with the capability gap requirement in the given mission area and its measure of performance. The measures of performance state what capabilities the new material solution must possess. These criteria will determine the number and type of systems more effectively.

Determining the number of systems a ship possesses (based on its mission sets), is challenging, and becomes more difficult when there are large defense cuts. Watson (1998, p. 374) stated the following concerning this issue:

> The difficulty facing naval staff when setting the design requirements for a warship is deciding whether to concentrate on single role such as anti-submarine or anti-aircraft or try building a multi-purpose ship has already been mentioned. The single purpose ship will be cheaper and may be better at its primary task but whether the exigencies of war will permit it to be used on for this task can be a matter of keen debate.

The tradeoffs between ship design and operational effectiveness are central to supporting a single role or multi-purpose platform.

I. OVERVIEW OF RELEVANT HUMAN SYSTEM INTEGRATION DOMAINS

Virtually all the domains of HSI are impacted by changes in ship design characteristics. This section of the literature review will consider the five most relevant domains and discuss several studies that describe the relationship between ship characteristics and HSI domains. In addition, alterations in the design characteristics that impact one HSI domain will impact other domains.

J. MANPOWER

In 2002, the Center for Naval Analysis conducted a study to assess the Navy's Manpower requirements (Moore, Hattiangadi, Sicilia, & Gasch, 2002). The study began by imposing five questions, but the four listed below are relevant to this thesis:

- "Is it possible to reduce shipboard manning while maintaining operational standards?"
- "What can a requirements process achieve? To what extent do Navy business practices support or undermine those functions?"
- "What are the main drivers of manpower requirements? Do those drivers make sense?"
- "How do private companies determine requirements? Might these practices be of value to the Navy?" (Moore et al., 2002, pp. 8–9).

The third question listed above, is the most relevant to this thesis. The main drivers for the manpower equation currently used by the Navy are based on workload. The primary workload categories are as follows:

- Operational Manning (OM)—Watch-standing

- Own Unit Support (OUS)—Those function unique to supporting the command
- Preventive Maintenance (PM)—Maintenance conducted to prevent corrective maintenance or avoid catastrophic failures of systems.
- Corrective Maintenance (CM)—This maintenance is not scheduled and typically requires a significant amount of labor.
- Facilities Maintenance (FM)—Those tasks conducted to maintain the ship (cleaning, painting, etc.).
- Productivity Allowance (PA)—20% allocation applied to observed workload with the exception of OUS, CM, and FM.
- Make Ready Put Away Allowance (MRPA)—30% applied to PM that are associated with gathering tools/supplies and making the system ready for operational usage
- Service Diversion and Training (SD&T)—Activities that lack productivity, but are necessary e.g., (quarters, inspections, ceremonies, etc.).

The factors utilized to make a manpower determination are influenced by the materiel solutions' attributes. The weakness of this evaluation of manpower is that it lacks analysis of ship's characteristics as key drivers. In order to be more effective at forecasting manpower, we would need to consider the baseline physical characteristics of a ship, as described by the previous section.

K. PERSONNEL

A 2011 study conducted by Navy Personnel Research, Studies, and Technology (NPRST) set out to evaluate the relationship between Sailors' aptitudes and their ability to multi-task (Hambrick et al., 2011). The researchers conducting this study posed the following hypothesis.

- Does the Armed Service Vocational Aptitude Battery (ASVAB) performance positively predict multitasking performance in a sample of U.S. Sailors?

The three abilities observed during the study were memory updating, task switching, and multitasking. The results supported the hypothesis that ASVAB performance predicts multitasking performance. Additionally, the ASVAB appeared to be capable of predicting

memory updating ability, as well as baseline and emergency multitasking. This study suggests that the personnel attribute of aptitude is a measure of overall productivity.

Another study, Morgan et al. (2011), sought to determine if civilian scholastic testing in combination with the Multi-Attribute Test Battery (MATB), could predict a person's ability to multitask. Participants were required to self-report Scholastic Aptitude Test (SAT) scores and American College Test (ACT) scores. Additionally, computer based versions of the following test were administered:

- Remote Association Task
- Scholastic Aptitude
- Working Memory
- Spatial Ability

Regression analysis was conducted utilizing the self-reported SAT and ACT scores in conjunction with computer based assessment tools. The results indicate that working memory and scholastic aptitude were critical for multitasking ability. This study suggests that other aptitude assessment tools besides the ASVAB are capable of identifying individuals with innate ability to multitask. Additional means of assessment may increase a military recruiter's ability to improve recruits' job fit and overall performance within their assigned job rating.

A key question is whether or not individuals can be more productive based on their aptitude. Ship design has the potential to generate a demand for individuals capable of handling a higher workload if manpower is constrained in the design of a new ship. Such a constraint would likely begin a domino effect that would impact other domains of HSI. For example, changing the length of a ship may decrease or increase manpower and lead to changes in habitability requirements such as berthing. In addition to changes in habitability, human factors engineering may be impacted due to the increased or decreased workload requirements.

L. TRAINING

Training's relevance must be appropriate for the environment in which those acquired knowledge skills and abilities will be utilized. The design and functional

capability of a ship is the operating environment considered for this study. For the purpose of this thesis, the three assumed factors that impact a vessel's complexity are as follows.

- Size of the ship: Displacement of the vessel
- Ship function: Task or mission driven
- Interdependent ship systems

A canoe, for example, is a comparatively small vessel with very little complexity; its major function is transportation. Training requirements are minimal. In contrast, an aircraft carrier is hundreds of times larger with thousands of crew members. Its complexity demands highly skilled sailors that require months of training and years of experience in order to perform as expected. One aspect of human performance is the ability to acquire and maintain situation awareness.

Situational awareness has been defined as, "perception of the elements in the environment within a volume of time and space, the comprehension of their meaning, and the projection of their status in the near future" (Endsley, 1995a, p. 65). Endsley's definition of situational awareness infers that as the volume of time and space increases, the more challenging it may be for the operator to gain and maintain situation awareness. The time required to train a shipboard operator is an enabler to rapidly comprehend the true status of a system.

Holland provides a superb explanation of how expertise gained through training and education reduces cycle time for building situation awareness when Waldrop (1993) summarizes Holland (1992) by stating:

> In the cognitive realm, says Holland, anything we call a "skill" or "expertise" is an implicit model-or more precisely, a huge, interlocking set of standard operating procedures that have been inscribed on the nervous system and refined by years of experience. Show a textbook exercise to an experienced physics teacher and he won't waste any time scribbling every formula in sight, the way a novice will; his mental procedures will almost always show him a path to the solution instantly.

Complex systems require a significant amount of understanding of how changes in system states impact the overall function of the system. The idea of Large-systems

operations, points out that operators must be capable of processing more information about system parameters while making appropriate decisions as operators. Endsley (1995) states the following regarding the complexity of systems:

> The operators of large, complex systems such as flexible manufacturing systems, refineries, and nuclear power plants must also rely on up-to-date knowledge of situation parameters and any patterns among them that might reveal clues as to the functioning of the system and future process state changes….. Without this understanding and prediction, human control could not be effective. (Endsley, 1995b, p. 33)

As systems become more complex, the expectation is that maintaining a high level of proficiency may require more training time, than less complex systems. Additionally, the operators of these large complex systems may require continual training to minimize the decay rate of skills.

As the complexity of systems increases onboard naval warships, more sophisticated training techniques have been used to help sailors achieve the requisite knowledge, skills, and abilities. The Littoral Combat Ship (LCS), based on General Accounting Office (GAO) report (2010), has adopted a "Train to Qualify" (T2Q) mentality as a means to qualify personnel before reporting to the ship. The T2Q philosophy integrates simulation-based training as a means to address training for a complex vessel like LCS. The connection between simulation and training is that simulations give the researcher a tool to determine how an operator would perform given a set of stimuli. Research using simulation is ideal for immersing the operator in a complex system and evaluating their response. Additionally, HSI practitioners can use simulation to determine how ship design characteristics may impact human performance during the research and development phase of the acquisition process.

Simulation has produced the same level of effectiveness as training on the actual platforms according to studies by Gopher and Bareket (1994), Jentsch and Bowers (1998), and Goettl and Shute (1996). Jenstch and Bowers (1998) found that low-fidelity training in simulation is effective if tasks are understood and properly designed into the simulation. Goettl and Shute (1996) studied the transfer of training between groups that receive part task training and criterion training (entire complex process) utilizing

simulation. This study's methodology may aid researchers in the determination of how a ship's design characteristics and operability impact task performance. Gopher and Bareket (1994) conducted a transfer of training study using a driving simulator. The study discovered that variable priority focus on two driving tasks led to increased performance on three actual driving scenarios. All three of these studies highlight the effectiveness of well designed simulation environments. The modeling of a virtual ship's operability based on ship characteristics may result in improvements in human performance. Simulation and training will most likely become a necessity rather than a luxury as we proceed to develop future complex systems.

The need to incorporate simulation based training into LCS sailors' training pipeline stems from the complexity of the platform. A 2010 GAO report highlights the need for a longer training pipeline. The report stated, "Our analysis of a sample of LCS positions showed that the number of training days required before an LCS sailor reports to the crew is significantly longer than for Sailors in comparable positions on other ships-an average of 484 days versus 126 days for an amphibious transport docking ship and 103 days for a destroyer" (GAO, 2010, p. 24). It is not clear that simulation-based training will minimize training, time but is necessary to provide sailors fully trained and capable of conducting operations at sea. This thesis does suggest that simulation-based training is capable of addressing training challenges associated with manning the next complex and highly capable warships.

M. HUMAN FACTORS ENGINEERING

Human factors in the maritime domain emerged from the need to improve safety and mitigate hazards at sea. According to Grech, Horberry, and Koester (2008), human factors in evolved over four eras and centered on preserving life at sea:

Early Days: hazards and shipping 1550s to 1800s

- 1800s to World War II: birth of international ship safety regulations
- World War II to the end of 1960s: beginnings of maritime human factors
- 1960 to Present day human factors

A central topic of human factors engineering is human error. One definition of human error states, “Human error is an inappropriate or undesirable human decision or behavior that reduces, or has the potential for reducing, effectiveness, safety, or system performance” (Sanders & McCormick, 1993, p. 656). In order to mitigate or eliminate undesirable human decisions, it is important to understand the link between decision making and ship design characteristics. This relationship is illustrated in the following excerpt, which takes place during the 1600s as a ship prepares to travel from the west coast of Goa, India to Lisbon, Spain:

> The reasons for the loss of so many over laden carracks in the Indian Ocean, and especially off the coast of Natal, have also been discussed above, and need only be recapitulated here. They were mainly due to willful overloading by the officers, passengers and crew, and to the superficial and inadequate careening[3] carried out during the ship’s stay at Goa. Contributory causes were inefficient stowage of the cargo; leaving Goa too late in the season; the crankiness[4] of the top heavy carracks; ships in a fleet parting company so as to reach Lisbon first and obstinacy of some of the pilots; and the inexperience of some gentlemen-commanders. (Brito, 1959, p. 25)

This excerpt hints at the negative consequences that result from the confluence of human decision making and ship design characteristics. Careening the ship is an example of a poor decision while crankiness is more related to the ship design characteristics.

In order to gain insight into the ship characteristics and mishap rates, accident data were requested from the Naval Safety Center. Mishap data from the last 10 years was requested and Table 1 shows the average number of mishaps across all ships in that class per year.

[3] Careening—“To moor a boat in the shallows so that when the tide falls the boat is left high and dry, for the purpose of cleaning and repairing the bottom” (Dictionary of English Nautical Language).

[4] Crankiness— “Describing a sailboat that heels easily in a breeze and will swamp or capsize if the sheets and helm are not carefully tended” (Dictionary of English Nautical Language).

Ship Class	Number of Ships in Class	2000	Total Mishaps	2001	Total Mishaps	2002	Total Mishaps	2003	Total Mishaps	2004	Total Mishaps	2005	Total Mishaps
Missile Guided Cruiser (CG)	22	0.8	18	0.7	16	1.4	16	1.0	23	1.8	39	0.7	16
Nuclear Aircraft Carrier (CVN)	10	5.4	54	4.2	42	4.7	42	5.8	58	5.2	52	4.0	40
Missile Guided Destroyer (DDG)	60	0.2	13	0.4	21	0.5	21	0.5	28	0.6	36	0.5	31
Missile Guided Frigate (FFG)	26	1.4	36	0.7	19	1.0	19	0.7	19	0.8	22	0.7	18
Landing Helicopter Assault (LHA)	2	8.0	16	3.5	7	5.5	7	6.5	13	3.0	6	4.5	9
Landing Platform Dock (LPD)	12	1.7	20	0.8	9	0.8	9	1.3	16	0.8	10	0.6	7
Patrol Craft (PC)	13	0.0	0	0.1	1	0.1	1	0.2	2	0.2	3	0.2	2

Ship Class	Number of Ships in Class	2007	Total Mishaps	2008	Total Mishaps	2009	Total Mishaps	2010	Total Mishaps	2011	Total Mishaps	20012	Total Mishaps
Missile Guided Cruiser (CG)	22	0.4	9	0.5	11	0.9	19	0.9	20	0.7	16	0.3	7
Nuclear Aircraft Carrier (CVN)	10	6.7	67	4.7	47	11.3	113	7.7	77	6.9	69	5.7	57
Missile Guided Destroyer (DDG)	60	0.8	47	0.7	39	0.9	54	0.7	43	0.8	46	0.4	25
Missile Guided Frigate (FFG)	26	0.7	19	0.6	16	0.5	14	0.6	16	0.8	20	0.3	7
Landing Helicopter Assault (LHA)	2	5.0	10	0.5	1	1.0	2	2.0	4	5.5	11	3.5	7
Landing Platform Dock (LPD)	12	1.8	21	0.4	5	0.4	5	1.3	16	0.7	8	0.4	5
Patrol Craft (PC)	13	0.1	1	0.1	1	0.0	0	0.2	2	0.0	0	0.0	0

Table 1. Average Number of Mishaps Across All Ships in Class Per Year

DDGs represent the majority of the ships in the sample while LHAs comprise the fewest. The longest ship is the CVN and the shortest is the PC.

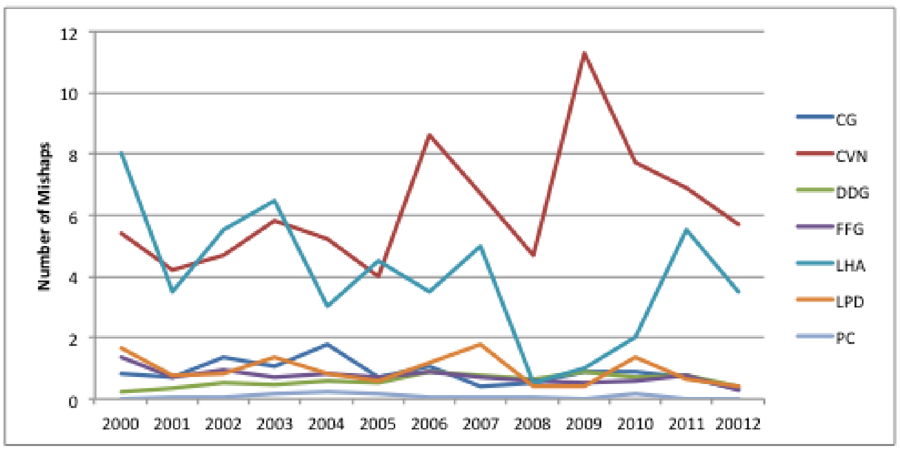

Figure 7. Average Number of Mishaps by Class Over the Past 10 Years

Figure 7 is a line chart representing mishaps by platform. Over the past 10 years, CVNs and DDGs reported the highest number of mishaps. The line chart indicates that CVNs and LHAs possess the highest mishap rates over the reporting period. The chart shows that larger ships (CVNs and LHAs) tend to have a greater number of mishaps.

CVNs are unique among all other warships sailing the seas of the world. CVNs conduct flight operations, possess nuclear reactors, steam turbines, and back up diesel generators. Additionally, this ship houses over 3,000 crewmembers that consist of the

ship's organic crew, and an air wing that embarks only for certification and deployments. LHAs have similar characteristics of the CVN, except for a nuclear reactor. LHA's conduct flight operations, possess steam powered propulsion, and diesel generators. The crew consists of over 2,000 crewmembers, which includes the ship's organic crew, air wing, and civilians.

The smaller class ships such as DDGs, FFGs, and PCs do not necessarily lack complexity in their design, but they all contain smaller crew complements. Both DDGs and FFGs conduct flight operations, but they are limited to only helicopters vice fixed wing aircraft that land on CVN and LHA platforms. DDGs and FFGs also use gas turbine propulsion, while FFGs also require diesel engines to supply the vessels' electrical distribution system. PC operations are limited to only small boat operations and do not support flight operations. PCs also use diesel engines for both propulsion and electricity distribution.

A few assumptions can be made regarding large ships and platforms based on their size, mission areas supported, and complexity of design in comparison to smaller ships. First, a large ship is likely to have more systems to monitor and therefore require more manpower. Second, the additional manpower is required for watch-standing, system monitoring, and maintenance. Third, these manpower levels must be maintained so that crews can obtain sufficient rest when deployed. If any of these assumptions is not true, will the impact be more significant on larger ships (with more systems and larger crews) or on smaller ships? The data suggest that larger platforms with more systems and more personnel experience a larger number of mishaps, presumably as a result of a greater number of human errors. However, there are steps that can be taken to mitigate the occurrence of human error or mishaps.

According to Sanders and McCormick (1993), three strategies can be employed to compensate for human error.

- Personnel Selection
- Training
- System Design

The three strategies employ the disciplines of both the HSI and systems engineering. The selection of the right people with the appropriate knowledge, skills, and abilities is essential to operational performance and mitigation of errors. Training developers must keep in mind the capabilities and limitations of human cognition and decision-making of the target audience. In addition, both personnel selection and training practitioners must be cognizant of the context (i.e., the platform for which personnel are being selected and trained). Sanders and McCormick (1993), mention design approaches to mitigate human error.

- Exclusion Designs—Committing errors is impossible
- Prevention Designs—Difficult to commit an error, but not impossible
- Fail-Safe Design—Reduces the consequence of errors

Based on HFE considerations discussed, it may be possible that ships of the past were unknowingly designed to be fail-safe systems. The use of fail-safe design only seeks to reduce the consequences of error, and not the probability that error will occur. For example, the use of an exclusion design for a de-watering system on a small boat makes more sense than a fail-safe design. If it is impossible to improperly start the de-watering system the small boat has a higher probability of survival. The fail-safe design may reduce the consequence by not damaging an improperly started system, but the small boat may take on a significant amount of floodwater. As time progressed and major catastrophes occurred at sea, like the Titanic and Exxon Valdez, ship designers have made a concerted effort to design ships with a high degree of exclusion and prevention system designs. The effort to design ships capable of compensating for human error or accidents at sea were driven by the maritime domain's adoption of the safety management system or International Safety Management (ISM) Code (Grech, Horberry, & Koester, 2008, p. 145). The ISM code established international standards for both the management and operations of ship.

As systems continue to become more complex and science and technology advance at exponential rates, we must have a paradigm shift to address error in more complex systems. The concept of "Resilience" is defined by Woods (2006) as how well a system recovers from disruption. Consider a very large and complex system with many

redundant components and sub-systems to ensure a ship function is not disrupted (e.g., the electrical distribution grid on ship, which is designed to withstand a significant amount of disruption prior to being inoperable). Although humans are a source of error and disruption, Woods argues that operators and their innate ability to adapt that are critical to mitigating system disruption.

> When researchers in the early 1980s began to re-examine human error and collect data on how complex systems had failed, it soon became apparent that people actually provided a positive contribution to safety through their ability to adapt to changes, gaps in system design, and unplanned for situations. Hollnagel (1983), for instance, argued for the need of a theory of action, including an account of performance variance, rather than a theory of 'error', while Rasmussen (1983) noted that 'the operator's role is to make up for holes in designers' work. (Woods, 2006, p. 4)

This statement proposes that larger complex systems benefit from the variance of operators, which may hint at why larger ships with complex systems are more resilient. This may also be an indication of why manpower shortages contribute to higher mishap rates as concluded by Lazzaretti (2008).

The next portion of the literature review consists of a brief historical perspective of ship design with commentary on its impact on HSI. The history reveals how changes in maritime technology impact the domains of HSI.

N. HISTORICAL PERSPECTIVE OF SHIP DESIGN AND HSI

Ship design has a long and intriguing history. A ship can be viewed as an extension of the human being itself. Ruskin made a thought-provoking statement when he said, "Take it all in all, a ship is the most honorable thing a man has ever produced" (Ruskin, 2011). The history of ship design reveals a close relationship between a variety of HSI domains and engineering considerations and suggests a roadmap for the evolution of ship design in the future. This historical perspective will address the evolution of ship design by examining technological advances and their interaction with HSI domains.

1. Pre-Age of Sail

Prior to the era of sail, humans most likely traveled the waterways utilizing anything that could float (George, 1998). The design necessary solely for water transportation depended primarily on the buoyancy of the material available. Around 3500 B.C., a human was, typically the designer, builder, and operator of his (or her) own method of waterborne transportation. Creativity and innovation were essential to survival and exploration of the environment. Our ancestor's transportation requirements for waging war and conducting commerce began the evolution of the personal watercraft that eventually led to the modern day ship. (Woodman, 1997)

The first boat (3000–2500 B.C.) was propelled by paddles and then, eventually, oars. The earliest boats called dugouts, were essentially logs hollowed out to transport passengers and stores. These small boats were limited by the amount of resources available in the environment. Manpower may have been plentiful to build and propel these small boats, but resources may have been scarce depending on the environment. Personnel issues could have arisen among the early operators of these vessels as well. Those individuals capable of building and propelling these vessels were likely to b highly valued in that society. Additionally, the transfer of knowledge and training to bring about innovations and mass production of small boats would have been critical to survival. Therefore, the era prior to sail was propelled by the need for increased capacity and reliability. A ship's capacity is manifested in its overall volume, and reliability was equated to a vessel's ability to resist deterioration from the environment and retain its buoyancy over time.

2. Age of Sail

The age of sails had a humble beginning. It is likely that sails emerged along the Nile River around 3500 B.C. (George, 1998). The main reasons for this innovation were to save energy and reduce manpower requirements. Fuel efficiency during this era was tied to manpower and food reserves vice the current day dependence on fossil fuels for propulsion. When Menes became the first Pharaoh of Egypt (around 3400 B.C.), sailboats were utilized for transportation of goods (Woodman, 1997). The innovation of the bipod

mast erected to support sails may have contributed to additional manpower requirements onboard. Increased manpower requirements are based on archeological artifacts that lead one to conclude that more effort and personnel were needed when ships evolved from monopod or single mast to a bipod mast system (Faulkner, 1941).

The integration of oar propulsion with wind sails may have contributed to survivability of warfighters due to conservation of energy that would have been used for rowing. Additionally, the Egyptians would have potential human factors and ergonomics challenges building boats that support both oar and sail powered propulsion.

The next evolution of the sail was the development of the lateen sail. The lateen sail was triangular and required both a mast and yardarm. The development of this sail is attributed to the Arabs around 500 A.D. (George, 1998). The development of this type of sail increased cost and manpower requirements. This claim is supported by George (1998) when he stated, “A disadvantage is that lateen sails require more sailors for tacking, making them more expensive to operate” (p. 40). This new evolution in sail design created a requirement for increased manpower, which increased operational costs. Despite the increased cost and manpower, the newly developed sail configuration was more efficient sail with the wind or with the wind at your back. Additionally, one could conclude that new technology creates a demand for newly skilled or trained individuals to operate newly designed vessels.

The next major milestone in early ship propulsion leading up to the “Ship of the Line,” was the development of full rigged ships or carracks, which first appeared around 1400 A.D. George (1998) states this was a major leap in technological advancement moving toward the warships of the 15th–18th century.

> The carrack is important in the progression of the warship development for two reasons. First, it served as the transition from the single to full-rigged three-masted ship after 1400 and second, after 1500, as the transitional ship for finally making guns at sea a significant factor. (George, 1998, p. 43)

A noteworthy observation is that the significant increase in the size of vessels coincides with the technological advancement of the fully rigged ship. Woodman (1997) supports the claim that both hull and sail increases occurred in tandem:

> it is clear that an additional forward mast was later the means by which greater sail was added to the increasing size of hulls. For despite impressions to the contrary, the big lateen required a larger crew to handle it. (Woodman, 1997, p. 53)

Once again, there is evidence that these technological advances led to increases in the level of manpower required to conduct operations.

As the evolution of sails progressed, the complexity of the rigging advanced as well. The increased complexity of ship rigging made human factors engineering and training a constant challenge. French constructor Jacques-Noel supports the claim that human factors and training were a major impact to the performance of a ship.

> It has often appeared that the best sailors [of the British] have been found to be of French origin....they have obtained this result of sailing particularly in our old frigates, by lightening their armament, reducing the length of their masts, diminishing proportionally their ballast, and increasing, in a remarkable manner, the depth of their false keel. (Ferreiro, 2007, p. 179)

This statement, if accurate, suggests that ship design characteristics, human factors engineering, and training may explain why sailors of French origin perform better than those of British origin. However, it is important to point out that this claim was made in the absence of an analysis of personnel attributes.

3. Naval Artillery in the Age of Sail

About 100 years after the development of the fully rigged ship, guns became a key component of war at sea. The number of guns a ship possessed eventually became the benchmark for which a “Ship of the Line” was classified. Naval artillery evolved over the years and still continues to evolve to this day.

There are two key design considerations regarding naval guns relevant to the age of sail. First, naval guns or cannons where constructed of either bronze or iron. And second, the guns were either loaded via breech or muzzle. The shift in material and procedure for loading cannons had many HSI domain implications.

The material selected for the cannon construction probably contributed to overall ship performance. Bronze is a heavier and weaker metal than iron. The utilization of a heavier metal with low reliability impacted multiple HSI domains. Personnel were required to lift a heavier metal while loading and unloading cannons. The use of heavier metal required selecting stronger personnel. Another issue was the higher incidence of a bronze cannon failing or exploding because bronze was less reliable than iron. The decision to use bronze or iron to make cannons would seem to be a materiel decision but such a decision clearly has HSI implications. In this case, using bronze in the cannons was more likely to lead to increased occupational safety hazards and decreased crew survivability.

In addition to material selection, the loading procedures for cannons impacted HSI domains. Toward the end of the 14th century, guns transitioned from breech-loaded to muzzle-loaded cannons. Breach loaded cannons required more training and maintenance due to the design's complexity. Muzzle loading canons, however, required less maintenance and protected gunners from toxic fumes released from poor breech cannon seal designs. The shift from breech to muzzle loaded cannons produced benefits from an occupational safety perspective and led to a reduction in manpower requirement, because muzzle loaded cannon designs were simplistic in comparison to breech-loaded cannons. Despite the benefits of the muzzle-loaded gun, there was a significant drawback. In order to reload the cannon, gunners had to expose themselves to hostile fire to move the cannon into the reloading position.

4. Age of Machine Propulsion

The age of machine propulsion came about in large part because of the requirement for increased speed (Woodman, 1997; George, 1998). Commerce became the fuel for innovation in ship design; in turn, machine propulsion made commerce viable

on a global scale. Wind power, despite being economical, was not always reliable. The development of new types of propulsion inevitably led to increased requirements in training, manpower, personnel, and human factors engineering.

a. Steam

Steam engines were the first major propulsion innovation. Robert Fulton was given credit for bringing steam engines to warships in America during the 1800s. This new innovation was met with resistance and much skepticism. The development and installation of steam engines onboard ships eventually improved speed, commerce, and ship warfighting capability.

Fulton's steam ship, the *Demologos,* was an innovative success, but an operational disaster. The *Demologos* was a steam powered paddle ship that rested on a dual catamaran hull and was the prototype for future ships of this class. Despite being a major accomplishment for marine technology, the vessel possessed many shortcomings.

> The engines were heavy, unreliable, inefficient and dangerous. They did not only make a mess and noise. They - and their nasty black fuel—took up cargo space in a merchantman and gun space in a warship. The fire risk was increased many times over. A paddler box made a large and vulnerable target And one round of a solid shot in the engine, or worse still the boiler—well it was best not to contemplate such a catastrophe. (Hough, 1969, p. 209)

Several HSI domain factors were impacted drastically by the new steam technology. The manpower requirements were extensive due to the lack of steam engine reliability and maintainability issues. As noted, the steam engine reduced space allocated for stores and weaponry. The introduction of steam propulsion introduced tradeoffs between habitability and propulsion that still impact modern warships. Occupational safety hazards were many due to exposure to toxic fuel, increased probability of fires, and steam plant explosions.

In order to address the vulnerabilities of steam paddle ships, screw propeller ships were developed by 1843. The first ship built in America was the *Princeton*, which was the second screw propeller ship in the world. Screw propeller ships presented a major advantage over their predecessors. The propeller was below the

waterline and therefore afforded better gun coverage and placement on main decks. Additionally, this new innovation provided a means to convert sail ships into steam-powered vessels. The conversion of ships from sails to steam and propellers had an impact on both habitability and manpower. Steam engine impacts to ship crew members were both positive and negative. The positive impacts were distilled water and the use of steam-powered machinery. The negative impacts were toxic coal dust, steam pipes that raised the internal ship space temperatures, and dangerous steam leaks in occupied work spaces (Sims, 2004).

The next evolution in ship design was the introduction of the Ironclad. The first Ironclad commissioned in 1861 was *HMS Warrior*. *Warrior* was considered the first modern warship and had a hull made completely of iron. Designing a ship made of iron was an attempt to increase the ship and crew's survivability against gunfire. Despite the gains in survivability, Ironclads did possess some disadvantages.

> There were two major problems with iron ships. First was their effect on the magnetic compass, which severely limited their use beyond rivers, lakes, and channel crossings. That problem was solved by Astronomer Royal Sir George Airey in 1839. The other, and for a warship more serious, problem was that iron was brittle, especially when cold. In a series of tests in the mid-1840s, iron-hulled ships did not fare well. (George, 1998, p. 67)
>
> One examiner concluded, "It has been proved that the disastrous effects of shot upon iron are so great that it is not a proper material of which to build ships of war. (Brown, 1990, p. 97)

In spite of the steam propulsion of iron-armored ships, they were still augmented by sails. This class of ship required proficiency in seamanship for sailing and the capacity to support steam propulsion systems below deck. Additionally, an iron ship was prone to corrosion and required significant maintenance. The era of the iron ship's eventually led to heavier Ironclads with higher propulsion capability. Significant increases in manpower occurred during the transition from wooden ships to Ironclads. Ironclad ships were covered in iron plating which required more maintenance than a

standard wooden hull. In addition, many Ironclad ships possessed hybrid sail and steam propulsion. This is another example of how technological innovations in ship design generally led to increases (rather than reductions) in manpower.

b. Diesel

The next innovation in propulsion was the introduction of the diesel engine. Successful demonstration of the diesel electric engine by Rudolph Diesel in 1898 led to a revolution in ship design. This innovation was a response to an increased demand for oil (Woodman, 1997). This increase in demand for oil generated a requirement for ships with a large capacity to transport huge stores of fuel oil. This innovation produced numerous HSI domain considerations.

One of the many significant HSI domains impacted by the introduction of the diesel was habitability (Watson, 1998). The diesel engine made economic sense and it improved the overall capacity of ships due to the reduced space requirements.

> The Selandia's voyage was a commercial success, proving the claims of her engine builders, that the diesel engine took up much less room than a steam reciprocating engine or steam turbine, each of which required only not boilers and bunkers, but tanks of fresh water. Moreover, the plant weighted less and required only a handful of greasers to attend to it, not an army of firemen who had by now, acquired a fearsome reputation as the most fractious members of a merchant ship's crew. (Woodman, 1997, p. 181)

As noted, the introduction of the diesel engine provided reductions in manpower due to fewer maintenance requirements compared to steam plants. The engine took up less space, therefore providing more room to support sailor habitability. A minor disadvantage of the diesel engine was personnel selection. The introduction of an electric drive diesel engine required a new classification for shipboard crew ratings. In addition to manning concerns, the lifecycle cost of selecting a specific propulsion method has major ramifications shown in Figure 8 (Watson, 1998, p. 265). The critical point to capture from the development of both the diesel engine and electric drive motor is that tradeoffs exist and have positive and negative implications. The tradeoffs that lead to the next

evolution in engine technology were based on the cost of fuel and manpower. The other consideration was the development of propulsion systems with a higher operational availability.

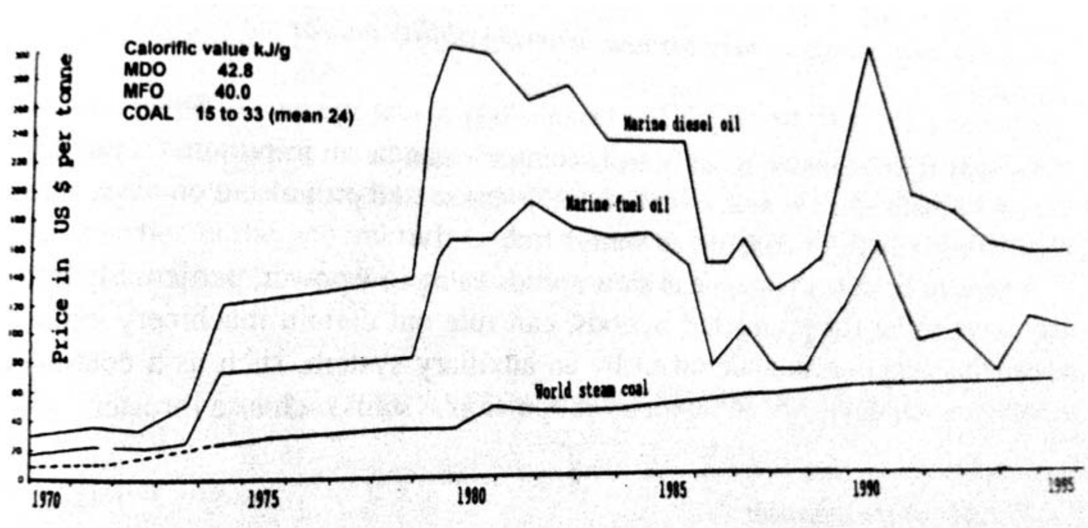

Figure 8. Fuel Prices through Years Based on Type of Propulsion

Since fuel oil became prevalent with the introduction of diesel engines, the search for more efficient engine technology led to the development of the gas turbine engine. For illustration, Figure 8 shows the cost of coal, diesel oil, and fuel over a period of 25 years. As world fuel oil production increased, it became more appealing fuel option, due to its lower cost in comparison to diesel oil. Therefore, development and operational usage of fuel-efficient gas turbine technology was a means to reduce operational costs.

c. Gas Turbine

As desired ship capability and requirements changed, ship architects and system engineers continuously had to innovate and develop new materiel solutions. The previous propulsion systems discussed provided the needed capability, but had many shortcomings. Key issues leading to the development of the gas turbine engine post WWII are summarized below (George, 1998, p. 256).

- Diesels
- Relatively large and heavy
- Disappointing at high speeds
    - High vibration issues with pistons
- Steam
    - Complex
    - Manpower-intensive (operations and maintenance)
    - Cost of manpower (during non-war periods)
    - Extensive start up time

The gas turbine engine was developed in 1930 by the Royal Navy. In 1966, it was adopted by the U.S. Navy in 1966 and installed onboard the Asheville class gunboats.

Gas turbine engines addressed the majority of issues that plagued its predecessors; steam and diesel engines. Rolls Royce Olympus turbines of the late 1960s were capable of 56,000 horsepower and a max speed of 30 knots for British class Amazon ships (Woodman, 1997). In addition to providing warships with increased speed and range, gas turbine engines have reduced the overall displacement of ships, allowing the installation of multiple engines for redundancy.

The introduction of gas turbine engines had major impacts for HSI domains. The reduction in manpower required for maintenance and operations proved to be effective in cost reduction. Also habitability was improved because innovation reduced engine space requirements. The range of gas turbine ships also increased stores requirements so support longer transits. One example of a high endurance platform is the CVN. A CVN is only constrained by the number of stores it has onboard to stay at sea due to its nuclear power plant. High endurance ships just like cruise liners, must give significant consideration to the habitability domain. In addition to habitability, the personnel domain should expect to see significant changes in training and personnel selection. Gas turbine expertise at that time was concentrated in the aerospace community. Due to the adoption of gas turbines at sea, the knowledge, skills, and abilities from the aerospace community will be implemented in the maritime domain.

The final advance in propulsion to be discussed in this literature review is nuclear propulsion. Admiral Rickover envisioned an all-nuclear powered Navy (Woodman, 1997).

d. Nuclear

The vision of an all-nuclear Navy made perfect sense because nuclear power provides an unlimited source of fuel for a ship's steam operated turbines. Nuclear powered ships were essentially the holy grail of propulsion but had many disadvantages.

Nuclear propulsion plants contain significant hazards to humans. The concerns of operating nuclear propulsion driven ships were so serious that national laws were passed to ensure protections were in place to mitigate a nuclear disaster. Nuclear reactors require shielding (in order to protect humans from gamma radiation), containment systems for breaches in the reactor, and safety devices and controls (designed to compensate for human error) (Tupper & Rawson, 2001). All the safety concerns surrounding nuclear propulsion create significant occupational safety concerns.

Another key consideration for the use of nuclear propulsion was the cost. Congress passed legislation supporting the use of nuclear reactors on all naval vessels that led to construction of the nuclear cruiser USS Long Beach and the nuclear carrier USS Enterprise (George, 1998). The plan to have nuclear propulsion for all naval vessels was short lived due to cost. Currently, the U.S. Navy only utilizes nuclear propulsion for aircraft carries because of its overall strategic capability.

The cost of a nuclear carrier is justified by the ship's requirements. The nuclear propulsion plant ensures that an aircraft carrier essentially has unlimited range and endurance. Another consideration is the space required to install a nuclear plant and stores necessary for the massive engineering department supporting nuclear operations. In addition to the nuclear reactor, the ship also requires steam turbines, which demand significant space for equipment storage and space. The requirement to have a ship anywhere in the world capable of projecting power ashore is what makes nuclear propulsion critical to our national strategy.

The introduction of the nuclear carrier led to a variety of tradeoffs across the domains of HSI. The massive space requirements for a nuclear powered aircraft carrier may provide more flexibility in tradeoffs between manpower and habitability. The nuclear power plant and steam turbines require a crew of more than 4,000 sailors. This large crew necessitates the berthing and stores to maintain operations for long periods of time. The type of personnel selected and the extensive nuclear training required to operate a complex system will drive overall life cycle cost. Additionally, the dangerous nature of operating a nuclear propulsion plant requires sophisticated human factors engineering to ensure crew safety while operating the plant.

5. Electronic Systems

Electronic systems are another attribute of ships relevant to this study. Electronic systems are monitored, operated, or maintained by humans. The acquisition of these systems helps build situational awareness or maintain it.

> The most sweeping post-World War II revolution has not been in weaponry but in electronics. Electronics became important in World War II, with many analysts concluding that Allied "sensing" systems such as sonar, radar, and direction finding played a larger role as any factor in defeating the Axis forces. System development has matured greatly in the postwar period thanks to better detection systems. The latest trend is extending electronics into command, control, and decision support. (George, 1998, p. 263)

Sensing systems are a ship characteristic that may or may not increase manpower requirements (Watson, 1998). The size or complexity of the ship potentially can be an indicator of the manpower and personnel requirements to maintain situational awareness.

O. PROPOSED HSI SHIP SYNTHESIS MANPOWER MODEL

Based on the findings of the historical perspective and variable discussion, this thesis proposes a HSI Ship Synthesis Manpower Model. This model extends the Paulo and MacCalam (2011) Ship Synthesis Model using the same framework shown in Figure 1 of this chapter.

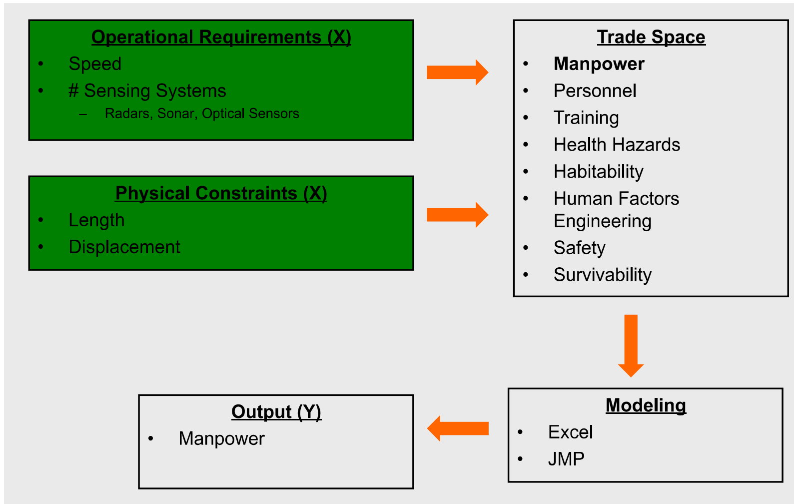

Figure 9. Proposed HSI Synthesis Manpower Model

The independent or input variables in the HSI synthesis model consist of two categories. The first category is the ship's operational requirements. The operational requirements are those traits that must be present in the final material solution. For example, a newly designed ship must be capable of defeating a missile with jamming capability. Therefore, the new ship will require radars large enough and powerful enough to fulfill the operational functions of tracking, frequency shifting, and targeting of an enemy missile simultaneously. The second category of variables is physical constraints. Physical constraints are those attributes such as length, displacement, and beam. The reason physical attributes are designated as constraints are because cost estimators have established and correlated cost models for ship physical attributes. Cost estimators do not determine constraints per se, but the limiting factor is the allocation of money in the defense budget. Based on this fact, cost models are a proxy for setting physical limitations on the ship design. The inputs based on requirements and constraints are then utilized to evaluate and quantify HSI domains in the trade space. The trade space is where HSI practitioners determine how interactions among the HSI domains are impacted by operational requirements and physical constraints. Once the impacts are quantified and evaluated through analysis, candidate response variables can be selected for modeling and forecasting.

This thesis represents and initial attempt to identify, select, and evaluate inputs as a part of an HSI Synthesis Model focused on the domain of Manpower. This research will help establish a process for the future modeling of all domains of HSI.

The literature review discussed the impact of ship design characteristics on the domains of HSI. The next step is the development of a quantitative model that will help system engineers and HSI practitioners forecast a manpower domain requirement based on operational requirements and physical constraints of the ship design. The next chapter will describe the methods used to develop a model to forecast manpower requirements based on ship characteristics.

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III. METHODS

A. METHOD OVERVIEW

The following research questions were addressed in this study:

- How do the domains of Human System Integration interact with the physical characteristics or design specifications of warships?
- How could the specified relationships between ship design and the domains of Humans Systems Integration be incorporated into the design of the OPV?
- Can a model based on the domains of HSI and ship characteristics predict or forecast HSI domain requirements?

This study analyzed a quantitative model, consisting of nine independent variables and one response variable. The first desired method of data analysis was multiple regression. However, due to the number of independent variables and small sample size, Principal Component Analysis (PCA) was necessary. Additionally, two independent variables, the block coefficient and Froude number may express collinearity because they share independent variables. PCA was used to accomplish the following:

> The central idea of principal component analysis is to reduce the dimensionality of a data set in which there are a large number of interrelated variables, while retaining as much as possible of the variation present in the data set. (Jolliffe, 2002, p. 1)

Once PCA was completed, the remaining variables were applied to a multiple regression model to predict the response variable (crew complement). The end result of this method yielded data showing which physical ship characteristics helped explain the variance in manpower predictions.

There were two reasons to focus on the response variable of crew complement (manpower). First, the literature review in Chapter II suggested that manpower requirements are closely related to the design characteristics of a ship. Second, manpower is one of the domains easiest to analyze because it is a quantifiable and continuous variable. This methodology did not seek to capture all of the variance to forecast manpower, but served as a complementary model to the Navy’s current shipboard Manpower model.

B. SAMPLE

1. Selection

The sampling procedure used by the researcher was purposive sampling. The sampling was purposive because the researcher was specifically modeling manpower for OPV. The sample size consisted of 35 patrol craft from the United States and 20 other nations. This class of ship was chosen to support the intent of the NICOP initiative. The sample selected makes no claim to be inclusive of every patrol craft vessel throughout the world, but contains the majority of prominent navies around the globe.

2. OPV Sample Characteristics

The characteristics of the OPV sample data are important to review because each nation has its own fiscal constraints and requirements to adhere to in the acquisition process. Additionally, it is useful to view this sample size within the context of the security challenges each nation faces. If the coastal security challenges are greater for one nation compared to another, that country most likely has more coastal patrol vessels represented in the sample.

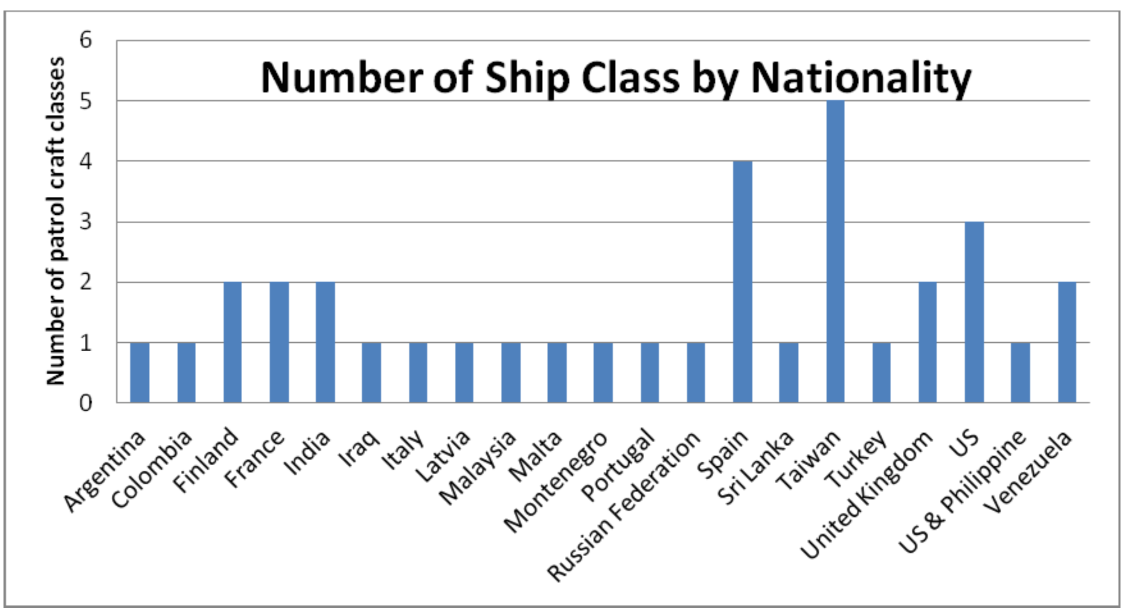

Figure 10. Distribution of Vessels Nationality

Figure 10 shows the number of patrol craft classes based on its nationality. The largest number of patrol craft represented in the sample is Taiwan. The majority of nations represented in the sample (13 of 21) have only one class of patrol craft. Five of 21 nations (Finland, France, India, United Kingdom, and Venezuela) have two classes of patrol craft.

Figure 11 shows the total crew complement based on nationality. France, Montenegro, and Turkey possess the largest crew complements. The smallest crew complement belonged to the nation of Latvia. The crew complement measures of central tendency and dispersion in the sample were (average = 55.60), (standard deviation = 5.71).

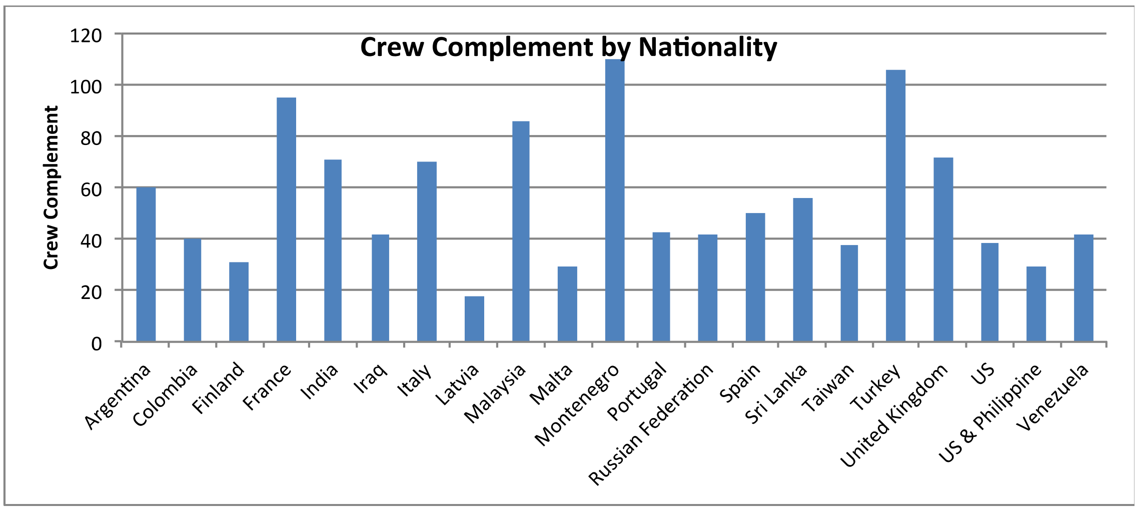

Figure 11. Crew Complement by Nationality

Figure 12 shows the ship length by nationality. The longest ships in the sample were France, Montenegro, and Turkey. The shortest ship length in the sample was Sri Lanka. The ship length measures of central tendency and dispersion in the sample were (average = 233.26), (standard deviation = 11.91).

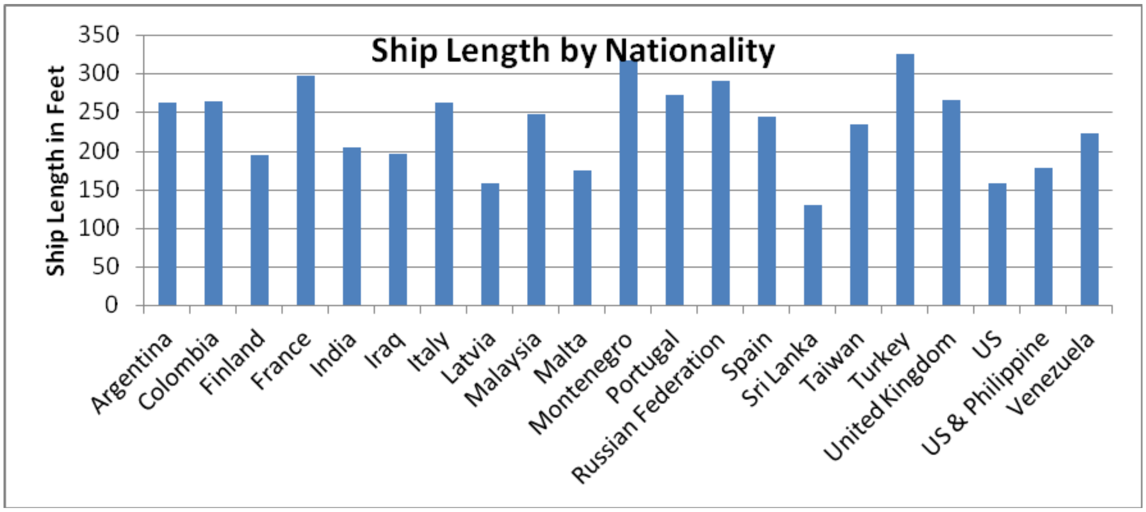

Figure 12. Ship Length by Nationality

Figure 13 shows the ship speed by nationality. The U.S. and Philippine patrol craft possess the fastest speed within the sample. The slowest speed within the sample was Finland. The measures of central tendency and dispersion for the sample were (average = 21.70), (standard deviation = 1.160).

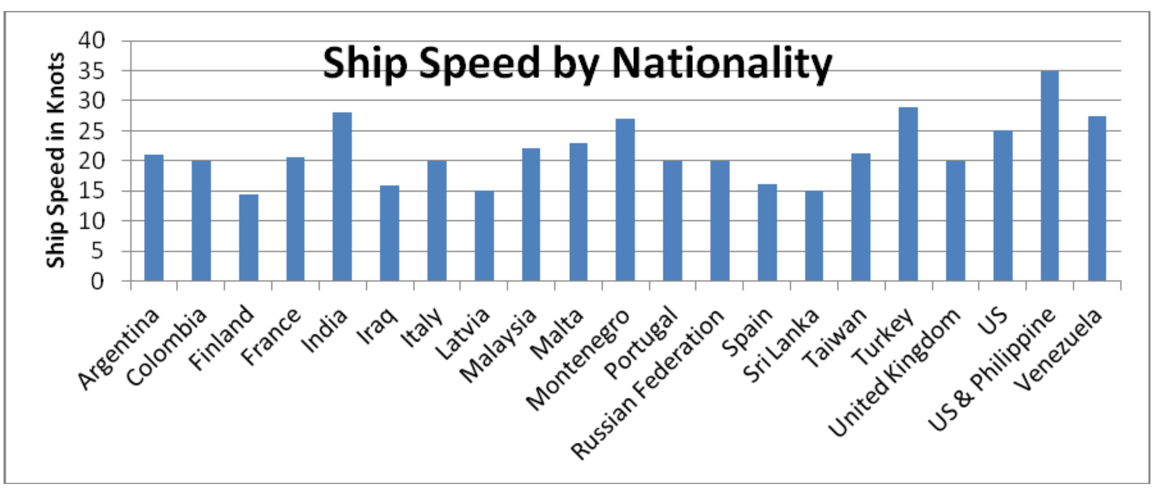

Figure 13. Ship Speed by Nationality

Figure 14 shows the ship draught by nationality. The United States and the Philippines have the deepest draught within the sample. The ship with the least amount of draught is Finland. The measures of central tendency and dispersion for draught were (average = 12.5), (standard deviation = .07).

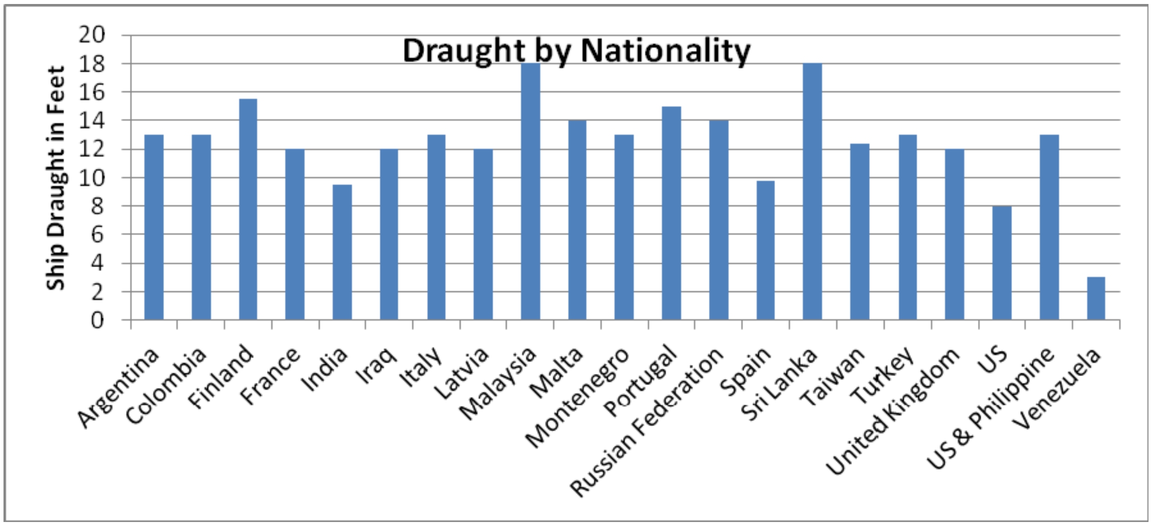

Figure 14. Draught by Nationality

C. MATERIAL

1. Analysis Tools

Microsoft Excel was used to analyze data from IHS Jane's database. Excel data sheets include the sample OPV data described in the previous section and additional charts developed for qualitative and statistical analysis. JMP version 10 was utilized to perform multiple regression and principal component analysis. Additionally, Parallels Desktop 7 Windows virtual operating system was used to support Excel data analysis features not operable on the Mac version of Microsoft Excel.

2. Equipment

- Macbook Pro 13-inch LCD screen
- Processor 2.4 GHz Intel Core 2 Duo

- 8 GB of RAM 1067 MHz DDR3
- Mac OS Lion 10.7.4/Windows XP via Parallels Virtual Desktop

D. DATA COLLECTION/PROCEDURES

The sample data were retrieved via the Naval Postgraduate School Dudley Knox Library Intranet. The database accessed to select the sample originated from the Information Handling Services (IHS) Jane’s Fighting Ships, which is a leading global provider of information and publicly accessible intelligence on military systems. These data were deemed to be as credible and accurate as possible while remaining unclassified. The data source utilized to compile this data came be deemed credible and accurate to its level of declassification. The researcher did not incur fees in order to access the IHS Jane’s database due to enrollment at NPS.

Once on the library intranet website, a database search was conducted. All database links are displayed for selection including a link to Jane’s Fighting Ships. Once in the IHS Jane’s website, the researcher conducted a search for OPV or patrol craft equivalents. The final sample selected by the researcher contained 35 ships representing 21 countries. All variables selected for analysis were based on research conducted in Chapter’s II literature review. The following ship design characteristics were selected from each ship:

- Displacement
- Length
- Speed
- Beam
- Draught
- Crew complement
- # of sensing systems (surface radar or optical camera)

Once the data were collected via IHS Jane’s, they were entered into an Excel database shown in Appendix A. In order to derive the block coefficient and Froude number, the researcher utilized the formulas discussed in Chapter II. In addition to those calculations, the researcher converted the following fields to meters to support calculation of the Froude number.

- Speed
- Draught (interchangeable with draft)

E. VARIABLES

1. Response Variable

The response variable selected for multiple regression analysis was manpower. Manpower was selected as the response variable because it is quantifiable and is an applicable HSI domain related to this thesis. The response variable is the overall crew complement of the ship, which was provided for each patrol vessel via IHS Jane's.

2. Independent Variables

The independent variables selected for the multiple regression analysis and principal component analysis were derived from the IHS Jane's database. In addition to the originally derived data, the block coefficient number and Froude number were calculated using ship theory formulas and Microsoft Excel.

- X_1 = Block Coefficient
- X_2 = Shaft Horsepower
- X_3 = # of Sensing Systems
- X_4 = Beam (Indication of Ship Volume combined w/ length)
- X_5 = Draught
- X_6 = Length (Similar to Beam)
- X_7 = Displacement (Thrust to weight ratio/Maneuverability)
- X_8 = Froude Number (Hydrodynamics)
- X_9 = Speed

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IV. RESULTS

A. PRINCIPAL COMPONENT ANALYSIS (PCA)

All data were entered into JMP version 10 and analyzed using JMP's PCA function. This analysis was necessary to eliminate factors in the data set that most likely would not account for the variance in the response variable (crew complement). This analysis will discuss results based on the correlation matrix, eigenvalues, and scree plot.

Correlations

	Diplacement (Tons)	Length (Feet)	Beam (Feet)	Max Speed (Knots)	Draft	Shaft Horsepower	Sensing Systems	Block Coefficient	Froude Number
Diplacement (Tons)	1.0000	0.8880	0.9216	-0.3279	0.5504	0.3926	0.2716	0.3411	-0.6551
Length (Feet)	0.8880	1.0000	0.9485	-0.0536	0.4781	0.6252	0.4200	0.1043	-0.4982
Beam (Feet)	0.9216	0.9485	1.0000	-0.2068	0.4866	0.4777	0.3076	0.1889	-0.5974
Max Speed (Knots)	-0.3279	-0.0536	-0.2068	1.0000	-0.3668	0.4230	0.3133	-0.5894	0.8820
Draft	0.5504	0.4781	0.4866	-0.3668	1.0000	0.0891	-0.0275	-0.2450	-0.5469
Shaft Horsepower	0.3926	0.6252	0.4777	0.4230	0.0891	1.0000	0.3692	-0.1441	0.0819
Sensing Systems	0.2716	0.4200	0.3076	0.3133	-0.0275	0.3692	1.0000	-0.0769	0.0789
Block Coefficient	0.3411	0.1043	0.1889	-0.5894	-0.2450	-0.1441	-0.0769	1.0000	-0.5427
Froude Number	-0.6551	-0.4982	-0.5974	0.8820	-0.5469	0.0819	0.0789	-0.5427	1.0000

Figure 15. Correlation Matrix for Independent Variables

The correlation matrix consists of the nine ship characteristics and 35 OPVs selected in the sample. The correlation matrix shows that four pairs of variables are correlated. Those correlated pairs are: {Displacement Tons, Length}, {Displacement Tons, Beam}, {Length, Beam}, {Speed, Froude Number}. Based on the correlation strength of each pair we expected some of these variables to be retained for the regression model.

Eigenvalues

Number	Eigenvalue	Percent	20 40 60 80	Cum Percent	ChiSquare	DF	Prob>ChiSq
1	4.1507	46.119		46.119	418.673	34.942	<.0001*
2	2.4741	27.490		73.609	330.978	33.183	<.0001*
3	1.1860	13.178		86.787	244.537	28.302	<.0001*
4	0.6501	7.224		94.011	181.480	21.779	<.0001*
5	0.3014	3.349		97.360	124.418	16.040	<.0001*
6	0.1607	1.786		99.146	83.778	11.073	<.0001*
7	0.0500	0.556		99.702	40.299	6.471	<.0001*
8	0.0236	0.263		99.964	22.788	2.806	<.0001*
9	0.0032	0.036		100.000	0.000	0.218	1.0000

Figure 16. Eigenvalues of Independent Variables

The next step in PCA required the interpretation of Eigenvalues. Figure 16 shows all components (PC) and their associated variance. PC 1 (displacement in tons) accounts for 46% of the total variance. PC 2 (Length in feet) accounts for 27% of the total variance. PC 3 (Beam in feet) accounts for 13% of the variance. The cumulative percentage of PCs 1-3 account for 86% of the variance combined. In addition to looking at the percentage of variance accounted for by PCs, the eigenvalues required interpretation. According to Marascuilo and Levin (1983), eigenvalues over 1.0 should be considered for retaining among those variables analyzed. Based on the threshold of 1.0 for eigenvalues, the PCs 1-3 should be retained for future analysis.

In addition to the evaluation of eigenvalues, a graphical analysis or scree plot was used to determine the number of variables to retain for future analysis. Figure 17 shows a graph with a plotted line demonstrating the relationship between PCs and eigenvalues. The interpretation of this plot is based on the shift in the slope from negative to flattening slope that approaches zero. Each dot on the trend line represents a factor or variable. The line shifts from a negative linear decline to flattening at the third dot, which indicated that three of the nine factors should be retained. This graphical analysis was consistent with the previous interpretation of eigenvalues shown in Figure 16.

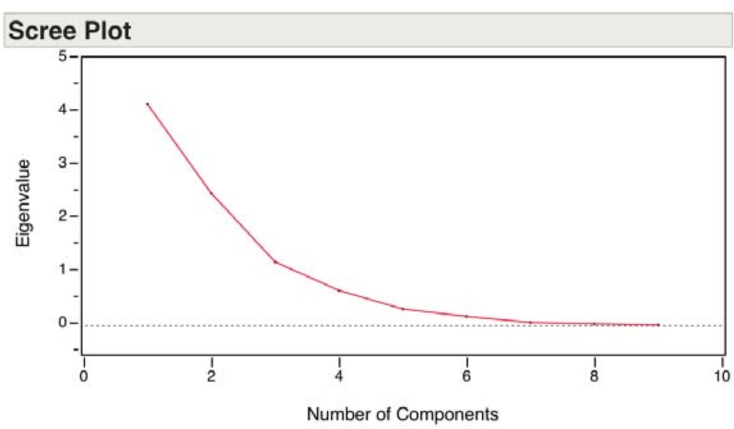
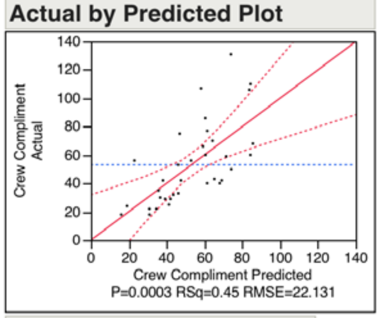


Figure 17. Scree Plot

B. MULTIPLE REGRESSION ANALYSIS

All ship sample data for three of the nine independent variables were entered into JMP version 10 database fields and a multiple regression model was fit to the data. The initial analysis shown in Figure 18 resulted in an R^2 of .45 and R^2 of .39 adjusted. The model accounts for 45% of the variance of the response variable (crew complement). The difference in the R^2 and R^2 adjusted is due to the non-significant terms in the model. The root mean square error (RSME), which indicates the average distance that a data point is from the fitted line, is very large indicating significant error in the model.

Actual by Predicted Plot



Summary of Fit

RSquare	0.451747
RSquare Adj	0.398691
Root Mean Square Error	22.13145
Mean of Response	53.02857
Observations (or Sum Wgts)	35

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	3	12511.132	4170.38	8.5144
Error	31	15183.840	489.80	Prob > F
C. Total	34	27694.971		0.0003*

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	-15.08261	30.26069	-0.50	0.6217
Diplacement (Tons)	-0.002542	0.011566	-0.22	0.8275
Length (Feet)	0.4279831	0.195476	2.19	0.0362*
Beam (Feet)	-0.73631	1.825496	-0.40	0.6895

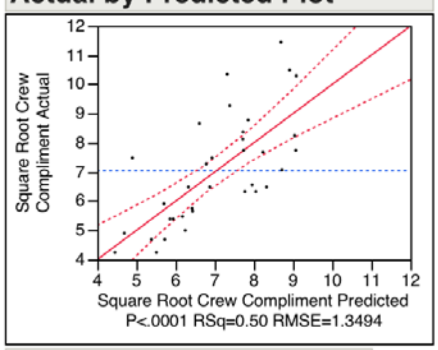
Figure 18. Non-Fitted Model

The next step consisted of fitting a multiple regression model without the non-significant terms displacement and beam. Prior to fitting the model, a data transformation of the response variable was conducted. The response variable was transformed to the square root of crew complement. The model suggested that the variable length has a

linear relationship with crew complement, but changing the scale of the response variable led to improvements in the model. The justification for data transformation was due to crew complement residuals failing to meet the normal distribution assumption.

The fitted model results shown in Figure 19 resulted in improvements in the model. The fitted model's R^2 of .49 and adjusted R^2 of .48 were a better fit compared to the previous model. The increase in R^2 may be due to the data transformation of the response variable. Additionally, the difference between $R^{2\ \text{and}}$ R^2 were reduced based on the removal of non-significant terms in the model. RMSE was reduced and the predictive values will perform better than the non-fitted model.

Actual by Predicted Plot



Summary of Fit

RSquare	0.499671
RSquare Adj	0.484509
Root Mean Square Error	1.349368
Mean of Response	7.042537
Observations (or Sum Wgts)	35

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	1	60.00714	60.0071	32.9566
Error	33	60.08618	1.8208	**Prob > F**
C. Total	34	120.09332		<.0001*

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	2.0840425	0.893339	2.33	0.0259*
Length (Feet)	0.0215314	0.003751	5.74	<.0001*

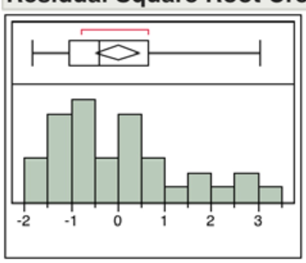
Figure 19. Fitted Model

The next step required validation of the following (Dixon & Massey, 1983, p. 173):

- Residuals must be normally distributed
- Residuals have a mean of zero
- Residuals have constant variance
- Residuals must be independent

The residuals from the fitted model, met all required assumptions, based on the researcher's analysis and interpretation of the residuals. Figure 20 illustrates the normality of distributed residuals. The majority of residuals fall within two standard deviations of the mean and the histogram did not appear to be skewed. Figure 21 illustrates the model's compliance with the assumption of constant variance. No pattern or funneling exists that indicated the residuals were exhibiting heteroscedasticity. The residuals appear to have a random (shotgun pattern) Figure 22 shows residuals by observation. The lack of a pattern was an indication that the residuals were independent and lack autocorrelation, therefore meeting the criteria for the final assumption.

Residual Square Root Crew Compliment



Quantiles

100.0%	maximum	3.0279
99.5%		3.0279
97.5%		3.0279
90.0%		2.26784
75.0%	quartile	0.64541
50.0%	median	-0.3928
25.0%	quartile	-1.0316
10.0%		-1.5241
2.5%		-1.841
0.5%		-1.841
0.0%	minimum	-1.841

Summary Statistics

Mean	3.553e-16
Std Dev	1.329376
Std Err Mean	0.2247056
Upper 95% Mean	0.4566566
Lower 95% Mean	-0.456657
N	35

Figure 20. Residual Distribution

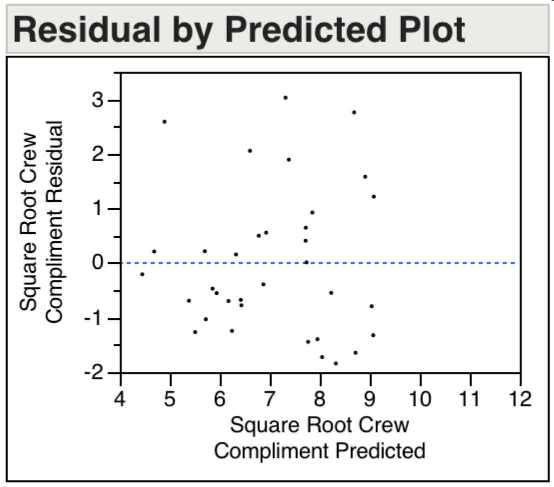


Figure 21. Residual by Predicted Plot

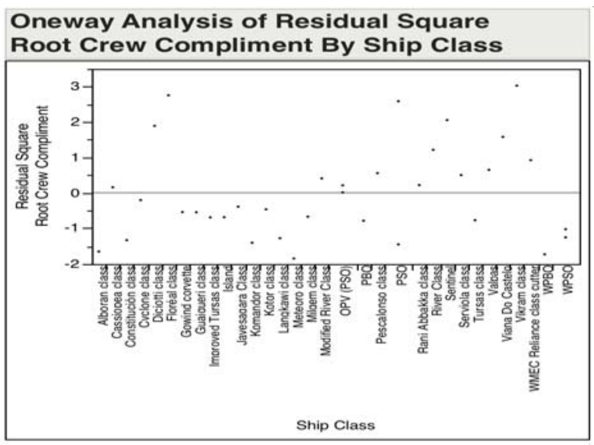


Figure 22. Crew Complement Residuals by Observation

B. MODEL APPLICATION

In order to evaluate how well the prediction equation or model is capable of forecasting manpower, a visual representation the data was necessary. Figure 23 illustrates the accuracy of this model. In the event this model was used to predict or forecast manpower requirements, the users must consider or mitigate risk for over or underestimating manpower requirements.

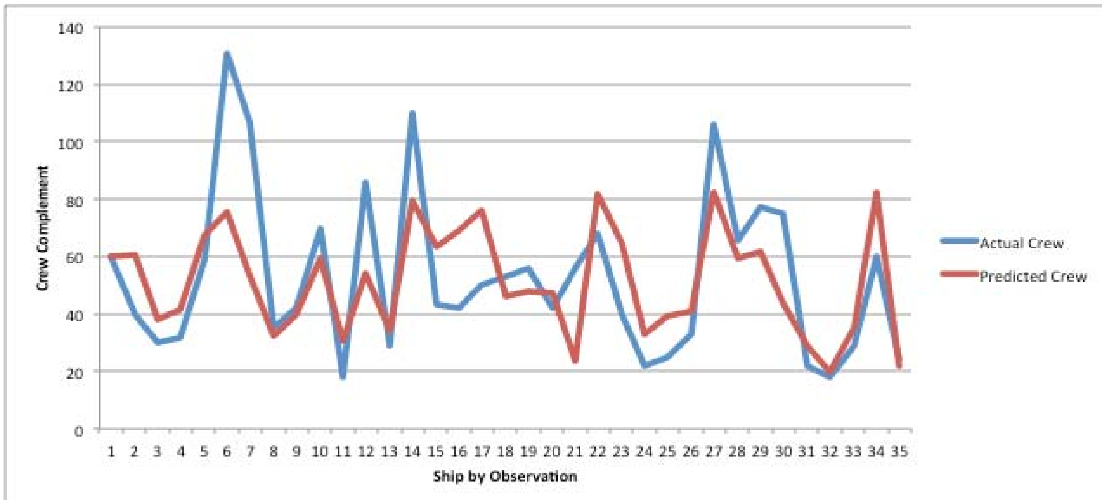


Figure 23. Actual Crew versus Predicted Crew

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V. DISCUSSION

A. RESEARCH QUESTION ONE

The concept that HSI domains interact with ship design characteristics appears to be supported. The literature review contains many examples and observations that describe how changes in technology impact multiple HSI domains. Additionally, the quantitative analysis demonstrated that ship characteristics are interrelated and impact the HSI domain of Manpower.

The literature review notes that both technology and operational requirements contribute to increases in manpower. George (1998) noted that an increase in manpower was necessary to operate lateen sails, which was a prelude to the development of bipod mast and eventually the “Ship of the Line.” The next technological advance that contributed to increased manpower requirements were steam propulsion. Hough (1969) mentions that early steam engines were unreliable and dangerous. The lack of reliability and the inherent dangerous operation of steam engines most likely led to increases in manpower. Additionally, it is logical to assume that systems with low reliability may require more man-hours allocated to support preventive and corrective maintenance. Further, the consequence of operating systems that pose high operational risk may increase the attrition of personnel due to injury and other occupational hazard risks. The next evolution in ship technology that may have contributed to manpower increases was the development of the Ironclad. Ironclads, as well as many other ships around the 1840s, possessed hybrid propulsion systems. The use of sail and steam propulsion in tandem on a vessel may have created a demand for skilled labor capable of tending to sails, steam engines, and iron plating maintenance. The solution to this problem would either require hybrid sailors or the addition of sailors to compensate for the organic sailors lacking in knowledge, skills, and, abilities.

In addition to the impacts of technological advances, we must also consider how modern technology is scalable. As technology increases in complexity and decreases in the space it requires, the size of a vessel may have more impact on HSI than in previous

eras. Woodman (1997) mentions that diesel engines occupied less space than their predecessors, the steam engine and steam turbine. Woodman's observation suggests that changes in maritime technology should not be measured solely by its capability, but also by the amount of space or volume it occupies.

The other factor contributing to interactions between manpower and ship design parameters were operational requirements. Woodman (1997) claims the era of machine propulsion was driven by speed requirements. Related to speed is a ship's long-term endurance at sea. Ships designed to conduct coastal patrol will most likely have less ship volume allocated to habitability and fuel storage. Both habitability and fuel storage are essential to a rapid transit across the open ocean. The ship class that embodies both speed and endurance is the CVN. This ship's maximum speed is classified and essentially has unlimited endurance at sea. The manpower requirements for this ship surpass every other ship in the U.S. Navy's arsenal of warships and allocate a significant amount of volume to habitability. Therefore, operational requirements manifest themselves in ship design and impact HSI domains.

The length of a ship, as noted in the data analysis, explains 49% of the variance in crew complement (manpower). The literature discusses the relationship between ship length and power requirements. Watson (1998) stated that an increase in ship length increases displacement, but reduces power requirements and fuel consumption. This may seem counterintuitive, but once a large ship generates momentum, it requires more resistance to slow it down. Watson's assessment of the relationship between length, propulsion, and fuel economy fails to mention tradeoffs with manpower. This thesis has established the relationship between the ship characteristic of length and domain of Manpower. Now that this relationship has been established, tradeoffs between ship length and manpower can be evaluated explicitly.

The quantitative analysis conducted in this study also supports Research Question One. Of the input variables selected to develop the manpower predictive model, ship length was statistically significant. Chapter IV provided insight into the correlation of ship length and manpower via Figures 11 and 12. Turkey, Montenegro, and France have

higher crew requirements based on their length, shown in Figure 11, and correspond to the data shown in Figure 12. This is not surprising since crew complement appears to be correlated with ship length.

B. RESEARCH QUESTION TWO

The idea that specified relationships between ship design and the domains of HSI can be incorporated into the design of the OPV is supported. This research question is supported because capability requirements impact both ship design parameters and HSI domains. One explanation for this finding is the strong connection between physical systems and cognitive processes and their impact on manpower requirements.

During the process of designing a ship, an OPV in this case, one must consider the capability requirements. If the capability-based assessment states that a newly designed OPV must be capable of speeds exceeding 35 knots, this requirement is likely to have HSI domain impacts. Unfortunately, speed was not a significant variable in this study, but the type of propulsion selected to achieve a speed of 35 knots interacts with ship length according to the literature review. Although a ship’s speed is not a significant predictor of manpower in this study, the literature review does suggest that propulsion requirements are related to ship length.

The discipline of Cognitive Science may be useful in explaining the link between physical systems and cognitive processes. This topic was not addressed in the literature review but is worthy of discussion to help explain how capability requirements and design parameters relate to manpower.

Cognitive Science is described as the science of how people interact with machines (Norman & Draper, 1986). Figure 24 is a visual depiction of Norman’s model of the Gulfs of Execution and Evaluation, which represents how humans interact with the physical system (in this case, the ship). The Gulf of Execution is a gap that exists between the goals of the human agent and the actions allowable by the physical system (Norman, 1988). The Gulf of Evaluation is the gap between what information was presented by the system and the interpretation by the human agent of the actual state of the system (Norman, 1988).

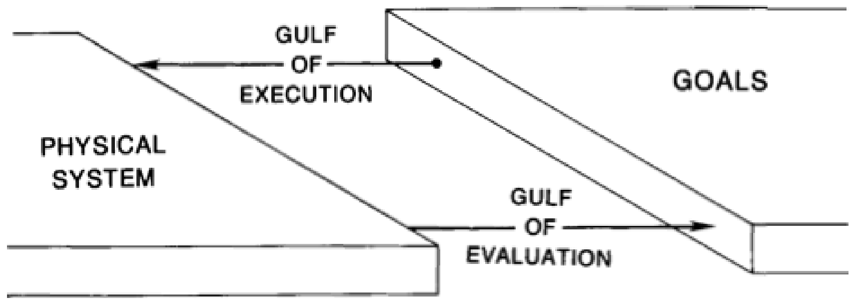

Figure 24. Gulfs of Execution and Evaluation (From: Hutchins & Hollan, 1985, p. 319)

An illustration of how Norman's model applies to ship design characteristics is a ship's detect to engage (DTE) sequence. Three tasks a ship must be capable of executing are detection, tracking, and engagement. Consider an aircraft or vessel approaching a ship at sea. The first step, detection, is accomplished by both a physical system acquiring the target and the operator tracking and classifying the contact. The second step is comprised of continuous tracking. The final step consists of engaging the target with a weapon system. All of these tasks require interaction between the system and operator. The Gulfs of Execution and Evaluation can be used to explain how the operator's interaction with, and interpretation of, a system's state affects operational performance. A physical system with large Gulfs of Execution and/or Evaluation may place higher demands on the cognitive resources of Sailors. When the cognitive demands of the tasks exceed the cognitive capacity of the Sailors, one solution is to increase manning, which will allow for the workload to be redistributed.

In the researcher's opinion, it would be faulty logic to suggest that a model consisting of only ship design parameters would account for all variance in manpower predictions. Therefore, Cognitive Science research will be critical in the development of more powerful manpower forecasting model. One research objective capable of supporting the development of manpower models is the comparison of cognitive workload among operators based on their ship class assigned. This research may aid in the understanding of how ship characteristics, manpower, and cognitive processes interact with one another.

C. RESEARCH QUESTION THREE

The question of whether a model consisting of ship attributes can forecast or predict manpower requirements can be answered in the affirmative. The HSI Synthesis Model developed as part of this thesis contained nine variables, one of which was evaluated empirically. The variable of manpower appears to be related to the Manpower domain. The length of a ship explains 49% of the variance in predicting manpower.

Both ship length and manpower (or crew complement) are related to cost. DoD employs a budgetary approach known as Cost as an Independent Variable (CAIV). CAIV is defined as, "methodology used to acquire and operate affordable DoD systems by setting aggressive, achievable Life Cycle Cost (LCC) objectives and managing achievement of these objectives by trading off performance and schedule, as necessary" (DAU, 2005). The development of a model capable of forecasting manpower requirements supports the requirements set forth in DoD Directive 5000.01, which state that fiscal constraints shall be considered in the acquisition process and cost will be viewed as an independent variable (Defense Technical Information Center, 2007).

When considering the design of a new ship, the established thresholds and objectives for ship parameters will likely influence manpower requirements. This thesis set out to address how those parameters would impact manpower. A manpower model based on ship attributes can aid in addressing two key questions. How will changes in the ship design increase or decrease manning? What are the long-term costs associated with designing this ship? Since manpower costs are an inescapable factor in the ship design equation, they must be modeled and considered in the acquisition process.

The final fitted model in this thesis provided some insight into how ship characteristics will impact the Manpower domain. This model must be viewed as an initial step toward understanding how ship design characteristics may influence all domains of HSI. Despite this model's ability to capture almost half of the variance in manpower it has three limitations. The first limitation is that this study only considered patrol craft in the sample of ships. The second limitation of this study is that cognitive processes and task-related functions were not included in the analysis. The third

limitation is that this manpower model contained a relatively small sample size in relation to the vast number of OPVs in service around the world. Despite all of the study's limitations, it establishes a baseline for future analysis of the relationships between ship design characteristics and the domains of HSI.

VI. CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

HSI is critical to the future of system engineering design and the DoD acquisition process. The study of how the physical environment impacts our human cognitive processes, physical activities, and performance is essential to maintaining military dominance. As fiscal constraints continue to impact defense spending, we must develop technologies and systems that reduce life cycle costs while improving or maintaining human performance. How do we achieve this objective? We can begin to reduce cost by understanding how ship characteristics impact HSI domains and designing systems commensurately. Throughout the literature review, the domains of Manpower, Personnel, Training, and Human Factors Engineering were discussed and found to be interrelated. Numerous examples were provided that illustrated the manner in which ship design characteristics interacted with these HSI domains. Moreover, in particular, this thesis demonstrated empirically, the relationship between the design characteristic of ship length and the HSI domain of manpower.

This thesis succeeded in accomplishing its three objectives. The first objective was the assessment of how ship characteristics impact the domains of HSI. This objective was accomplished through an historical perspective, discussion of ship theory, and design characteristics. The second objective was the evaluation of an HSI domain, given a set of ship characteristics. This objective was accomplished through quantitative analysis using PCA and multiple regression. The final objective was the development and assessment of a model capable of evaluating ship characteristics and a domain of HSI. This objective was accomplished through multiple regression and evaluation of the model's ability to predict manpower requirements. Overall, this thesis reveals that much work still needs to be done to identify and quantify many more relationships between ship design characteristics and HSI domain.

B. RECOMMENDATIONS

The modeling of relationships between ship design characteristics and domains of HSI appears to be a new area of research. The major challenge of modeling ship characteristics and HSI domains lies in the historical analysis of ship architecture, and design theory through the lens of HSI.

A shortfall of the present study was that it only considered one class of ship. This research analyzed data that consisted of OPV and patrol craft equivalent vessels. Future research should investigate multiple classes of ships with a larger sample size. Additionally, future research should incorporate more ship design characteristics as independent or predictor variables. For example, the number and type of weapons systems selected in the ship design may also influence manpower requirements.

Future studies should also consider incorporating the Navy's current manpower model. The framework of this model is constrained by the Navy standard workweek. (The Navy standard workweek is used to determine how many Sailors are required for a platform by identifying all of the work that must be accomplished. The current Navy standard workweek policy indicates Sailors should spend 81 hours per week engaged in work-related activities.) Incorporating the Navy standard workweek into the HSI Synthesis Model will provided a design parameter that will ensure manning levels are realistic.

Finally, the author encourages and the addition of other domains into the proposed HSI Synthesis Model for Ship Design. The addition of other HSI domains into the model may improve for the accuracy of the model and provide a valuable aid for conducting HSI domain tradeoff analysis.

APPENDIX A. IHS JANE'S OFF-SHORE PATROL VESSEL (OPV) DATA

Nation	Ship Class	Displacement Tons	Displacement (lbs) full load	Length (ft) overall	Beam (ft) overall overall	Max Speed (kts)	Max Speed (meters)	Crew Compliment	Draught Meters	Draught (ft)	SHP	# of sensing systems	Block Coefficient	Froude Number
Argentina	OPV (PSO)	2072.3	4144600	262.5	42.7	21	10.80333333	60	3.81	12.5	10950	3	0.51767057	0.212928005
Colombia	PSO	1899.3	3798600	264	43	20	10.28888889	40	3.81	12.5	10940	2	0.46846723	0.202211651
Finland	Improved Tursas class	1232.4	2464800	190	36	15	7.716666667	30	4.60248	15.1	3808	1	0.417625189	0.178769161
Finland	Tursas class	1399.9	2799800	202	33	14	7.202222222	32	4.84632	15.9	4360	1	0.46227736	0.161819366
France	Gowind corvette	1653.5	3307000	285.43	42.65	21	10.80333333	59	2.98704	9.8	8160	3	0.4850958	0.204196188
France	Floréal class	3303.6	6607200	306.76	45.93	20	10.28888889	131	4.29768	14.1	8820	3	0.582024431	0.187589608
India	Vikram class	1371.3	2742600	243	37	22	11.31777778	107	2.10312	6.9	10942	1	0.773648044	0.231844975
India	Rani Abbakka class	307.5	615000	168	27.6	34	17.49111111	35	3.5052	11.5	12800	2	0.201835224	0.430925724
Iraq	OPV (PSO)	1543.2	3086400	197	37	16	8.231111111	42	3.81	12.5	6300		0.592805597	0.187268621
Italy	Cassiopea class	1652.4	3304800	261.81	38.71	20	10.28888889	70	3.5052	11.5	7940	3	0.49622197	0.203055625
Latvia	Valpas	610.7	1221400	159.1	27.9	15	7.716666667	18	3.81	12.5	2000	1	0.385222432	0.1953594
Malaysia	Langkawi class	1456.2	2912400	246.06	35.43	22	11.31777778	86	3.68808	12.1	12720	3	0.483160619	0.230398854
Malta	Diciotti class	439.8	879600	175.2	26.57	23	11.83222222	29	5.39496	17.7	6335	2	0.186820421	0.285455838
Montenegro	Kotor class	2094.4	4188800	317	42	27	13.89	110	4.20624	13.8	18000	4	0.398969811	0.249122112
Portugal	Viana Do Castelo	2059.1	4118200	272.64	42.29	20	10.28888889	43	3.84048	12.6	10460	1	0.496075387	0.198981799
Russian Federation	Komandor class	2721.1	5442200	289.7	44.62	20	10.28888889	42	4.69392	15.4	7020	1	0.478424889	0.193034036
Spain	Meteoro class	3130.6	6261200	308	47	20.5	10.54611111	50	4.29768	14.1	12000	2	0.536819073	0.191891902
Spain	Alboran class	2199.1	4398200	218.18	36.09	13	6.687777778	53	4.38912	14.4	3250	2	0.67881075	0.144581933
Spain	Serviola class	1284.2	2568400	225	34	19	9.774444444	56	3.41376	11.2	7500	2	0.524591503	0.208084861
Spain	Pescalonso class	2353.4	4706800	222.44	36.09	12	6.173333333	42	4.69392	15.4	2460	2	0.666259331	0.132176104
Sri Lanka	Jayesagara Class	369.3	738600	130.58	22.97	15	7.716666667	56	2.10312	6.9	2180	1	0.624540493	0.215640868
Taiwan	PSO	2320.4	4640800	323	43	24	12.34666667	68	5.39496	17.7	19850	1	0.330359391	0.2193755
Taiwan	PBO	2042.6	4085200	277	41	20	10.28888889	40	4.60248	15.1	10890	1	0.416879749	0.197409594
Taiwan	WPBO	939.2	1878400	168.96	27.56	16	8.231111111	22	3.68808	12.1	2500	2	0.583415071	0.202211651
Taiwan	WPSO	1261	2522000	193.24	31.5	16	8.231111111	25	3.10896	10.2	13080	2	0.710845759	0.18908175
Taiwan	WPSO	783.7	1567400	201.44	31.17	30	15.43333333	33	3.90144	12.8	3000	2	0.341291448	0.347237437
Turkey	Milgem class	2239.9	4479800	325	47	29	14.91888889	106	3.59664	11.8	11580	5	0.434944104	0.264261844
United Kingdom	River Class	1903.7	3807400	261.65	44.62	20	10.28888889	66	3.81	12.5	11063	2	0.456568806	0.2031177
United kingdom	Modified River Class	2069	4138000	267.9	44.62	20	10.28888889	77	3.81	12.5	11063	1	0.484636637	0.20073439
US	WMEC Reliance class cutter	1124.4	2248800	210	34	18	9.26	75	3.2004	10.5	5000	1	0.524929972	0.204052068
US	Sentinel	395.7	791400	153.22	25.26	28	14.40444444	22	2.5908	8.5	5760	2	0.420984751	0.371602345
US	Island	188.5	377000	109.91	21	29	14.91888889	18	2.19456	7.2	6246	1	0.396999902	0.454420105
US & Philippine	Cyclone class	424.4	848800	179	25	35	18.00555556	29	2.40792	7.9	14400	1	0.420168305	0.429753748
Venezuela	Guaiqueri class	2613.6	5227200	324.46	44.62	24	12.34666667	60	3.81	12.5	23600	4	0.505482847	0.218881373
Venezuela	Constitución class	190.7	381400	121	23.3	31	15.94777778	24	1.79832	5.9	6000	3	0.401259599	0.462963926

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APPENDIX B. OPV CHART DATA—DISTRIBUTION OF VESSELS INCLUDED IN DATA ANALYSIS BY NATIONALITY

Nation	Number of Vessels
Argentina	1
Colombia	1
Finland	2
France	2
India	2
Iraq	1
Italy	1
Latvia	1
Malaysia	1
Malta	1
Montenegro	1
Portugal	1
Russian Federation	1
Spain	4
Sri Lanka	1
Taiwan	5
Turkey	1
United Kingdom	2
US	3
US & Philippine	1
Venezuela	2

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APPENDIX C. OPV CHART DATA—AVERAGE CREW COMPLEMENT BY NATIONALITY

Nation	Number of Crew
Argentina	60
Colombia	40
Finland	31
France	95
India	71
Iraq	42
Italy	70
Latvia	18
Malaysia	86
Malta	29
Montenegro	110
Portugal	43
Russian Federation	42
Spain	50.25
Sri Lanka	56
Taiwan	37.6
Turkey	106
United Kingdom	71.5
US	38.33333333
US & Philippine	29
Venezuela	42

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APPENDIX D. OPV CHART DATA—AVERAGE SHIP SPEED (IN KNOTS) BY NATIONALITY

Nation	Ship's Speed
Argentina	21
Colombia	20
Finland	14.5
France	20.5
India	28
Iraq	16
Italy	20
Latvia	15
Malaysia	22
Malta	23
Montenegro	27
Portugal	20
Russian Federation	20
Spain	16.125
Sri Lanka	15
Taiwan	21.2
Turkey	29
United Kingdom	20
US	25
US & Philippine	35
Venezuela	27.5

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APPENDIX E. OPV CHART DATA—AVERAGE SHIP LENGTH (IN FEET) BY NATIONALITY

Nation	Ship's Length (ft)
Argentina	262.5
Colombia	264
Finland	196
France	296.095
India	205.5
Iraq	197
Italy	261.81
Latvia	159.1
Malaysia	246.06
Malta	175.2
Montenegro	317
Portugal	272.64
Russian Federation	289.7
Spain	243.405
Sri Lanka	130.58
Taiwan	232.728
Turkey	325
United Kingdom	264.775
US	157.71
US & Philippine	179
Venezuela	222.73

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APPENDIX F. OPV CHART DATA—AVERAGE SHIP DRAUGHT (IN FEET) BY NATIONALITY

Nation	Ship's Draught
Argentina	13
Colombia	13
Finland	15.5
France	12
India	9.5
Iraq	12
Italy	13
Latvia	12
Malaysia	18
Malta	14
Montenegro	13
Portugal	15
Russian Federation	14
Spain	9.75
Sri Lanka	18
Taiwan	12.4
Turkey	13
United Kingdom	12
US	8
US & Philippine	13
Venezuela	3

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APPENDIX G. OPV CHART DATA: PREDICTION MODEL ACTUAL CREW VERSUS PREDICTED CREW

Actual Crew	Predicted Crew
60	59
40	40
30	32
32	34
59	58
131	162
107	147
35	35
42	40
70	67
86	99
29	30
43	42
42	41
50	49
53	45
56	52
42	39
56	48
68	78
40	40
25	29
33	33
66	63
77	75
75	66
22	22
18	18
29	27
60	65
24	23

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